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(54) Title: DIFFRACTION GRATING-BASED WAVELENGTH SELECTION UNIT

(57) Abstract: An optical wavelength selection apparatus containing a surface-relief transmission diffraction grating, a collimating lens for collimating a beam incident to the diffraction grating, and a focusing lens for focusing the beams diffracted by the diffraction grating. The diffraction grating, after having been subjected to a test condition of 85 degrees centigrade and a relative humidity of 85 percent for at least 500 hours, has diffraction efficiency performance within 6 percent of that achieved before being subjected to hese test conditions.

Description

Diffraction Grating-Based Wavelength Selection Unit

Technical Field

A diffraction grating-based wavelength selection unit.

Background Art

Surface-relief reflection grating elements are well known to those skilled in the art. The properties of surface-relief reflection grating elements are disclosed in Christopher Palmer's "Diffraction Grating Handbook," Fourth Edition (Richardson Grating Laboratory, Rochester, New York, 14605).

While surface-relief transmission grating elements are not as well known or used as surface-relief reflection grating elements, they are commercially available from Holotek LLC of Henrietta, New York. Surface-relief transmission grating elements have the same advantages that surface-refleif reflection grating elements have; and they provide even more advantages than surface-relief reflection grating elements when used in fiber-optic communication devices. In particular, they can provide higher wavelength dispersion power while still achieving essentially equal diffraction efficiency values for S and P polarized optical components. However, when the grating surfaces of prior art surface-relief transmission grating elements are subjected to a temperature of 85 degrees centigrade at a relative humidity of 85 percent for two hours or less, the grating surfaces are degraded until the grating structure disappears. This test is often referred to as the "Bellcore High Temperature High Humidity Storage Test for Fiber Optic Devices."

It is an object of this invention to provide a surface-relief transmission grating with improved durability when subjected to the Bellcore High Temperature High Humidity Storage test conditions.

It is yet another object of this invention to provide devices incorporating such improved surface-relief transmission grating.

Disclosure of the invention

In accordance with this invention, there is provided an optical wavelength selection apparatus containing a surface-relief transmission diffraction grating, a collimating lens for collimating a beam incident to the diffraction grating, and a focusing lens for focusing the

beams diffracted by the diffraction grating. The diffraction grating, after having been subjected to a test condition of 85 degrees centigrade and a relative humidity of 85 percent for at least 500 hours, has diffraction efficiency performance within 6 percent of that achieved before being subjected to these test conditions.

Brief description of the drawings

The claimed invention will be described by reference to the specification, and to the following drawings in which like numerals refer to like elements, wherein:

Figure 1 is a partial sectional view of one preferred transmission grating element of the invention;

Figure 2 is an enlarged view of a portion of the transmission grating element of Figure 1;

Figure 3 is a flow diagram illustrating one preferred process for preparing the transmission grating element of Figure 1;

Figure 4 is a graph illustrating the effect of varying the ratio of certain grating characteristics upon grating diffraction efficiency of the transmission grating element of Figure 1;

Figure 5 is a schematic illustrating a spectrophotometer which utilizes the transmission grating element of Figure 1;

Figure 6 is a schematic of a spectrophotometer which utilizes the transmission grating element of Figure 1;

Figure 7 is a schematic of a dual pass grating-based wavelength selection unit which utilizes the transmission grating element of Figure 1;

Figure 8 is a schematic of another dual pass grating-based wavelength selection unit utilizing the transmission grating of Figure 1;

Figure 9 is a schematic of yet another dual pass grating-based wavelength section unit utilizing the transmission grating element of Figure 1;

Figures 10A and 10B are side and top views, respectively, of a transmission grating-based demultiplexer fiber-optic unit;

Figure 10C is a schematic view of the fiber-optic input/output array used in the demultiplexer of Figures 10A and 10B;

Figures 11A and 11B are side and top views, respectively, of a transmission grating-based fiber-optic spectrophotometer unit;

Figure 11C is a schematic view of the fiber-optic input/output array used in the spectrophotometer of Figures 11A and 11B;

Figure 12 is a schematic view of a dual pass grating-based wavelength section unit that utilizes the transmission grating of Figure 1;

Figures 13 and 14 each present a schematic of a spectrophotometer which utilizes the transmission grating of Figure 1;

Figures 15, 16, 17, 18, 19, 20, 21, 22, 23 and 24 each present a schematic of a surface-relief grating-based device which utilizes physically cascaded grating elements;

Figures 25A, 25B, and 26 illustrate wavelength-division add/drop multiplexer devices that incorporate the dual cascaded grating element of Figure 20;

Figure 27A is a schematic side view of a transmission grating-based demultiplexer fiber-optic unit;

Figure 27B is a schematic top view of some the optical components used in the demultiplexer device of Figure 27A;

Figure 28 is a schematic of yet another dual pass grating-based wavelength section unit utilizing the transmission grating element of Figure 1.

Best Mode for Carrying out the invention

Figure 1 is a sectional side view of a preferred sinusoidal surface-relief transmission diffraction grating element 10 comprised of a substrate 12 and a grating forming layer 14 containing surface-relief diffraction grating 15. This Figure 1 illustrates the angular relationship between the incident optical beam 1 and the diffracted optical beams 2,3 relative to the normals 4,5 to the grating surface for this grating element 10. The incident beam 1 is comprised of λ_1 and λ_2 wavelength components and makes an angle of θ_i with the normal 4 to the substrate surface. After propagating through the substrate 12 and grating forming layer 14, the beam 1 is incident on the surface-relief grating 15. A portion of the incident beam 1 intensity is undiffracted and exits the grating as the zeroth order beam 6 at an angle θ_o relative to the grating normal 5, while the remaining beam intensities for each of the wavelength components of beam 1 are diffracted into first order λ_1 wavelength beam 2 and

first order λ_2 wavelength beam 3 having angles of θ_d and $\theta_d + \Delta\theta_d$, respectively, with regard to the grating normal 5 for the case where $\lambda_2 > \lambda_1$. Because, in the embodiment depicted in Figure 1, the grating forming layer 14 is parallel to the substrate surface on which it resides and the substrate 12 has parallel surfaces, one does not have to include the index of refraction of either the substrate or grating forming layer into the grating equation used to calculate the angular relationship between incident and diffracted beams for the grating element 10. Under the parallel plate conditions depicted in Figure 1, θ_i can be used as the incident angle in the grating equation and, therefore, the undiffracted zeroth order beam makes an angle of $\theta_o = \theta_i$ with regard to the normal 6 to the grating surface.

The surface-relief diffraction grating illustrated in Figure 1 is a surface-relief transmission diffraction grating, i.e., a transparent diffraction grating that serves to transmit light. Surface-relief diffraction gratings are well known and are referred to in, e.g., United States Patents 6,157,042 (metal surface-relief diffraction grating with a gallium arsenide substrate), 6,108,135, 5,569,904, 5,539,206, 5,363,226 (surface-relief reflection diffraction grating), 5,162,929, 5,089,903, 4,842,633, 4,206,295, 4,204,881, 4,289,371, 4,130,347, 4,057,326, and the like.

The substrate 12 is a transmissive material, i.e., a material with a transmittance (the ratio of the radiant power transmitted by an object to the incident radiant power) of at least about 70 percent for the wavelength spectrum to be used with the grating element. In fiber-optic telecommunication devices, such wavelength spectrum is generally from about 1280 to about 1620 nanometers.

The substrate 12 preferably is of high optical quality, i.e., it introduces less than 0.25 wave of either spherical or cylindrical wavefront power into the transmitted beam; the term wavefront power is discussed in United States Patent 5,457,708, 5,264,857, 5,113,706, 5,075,695, and 4,920,348. This means that the preferred substrate 12 has flat surfaces which, in one embodiment, are preferably substantially parallel to each other, that is, being parallel within about 1 arc minute of each other.

The substrate 12 is preferably optically homogeneous, i.e., all components of volume in the substrate 12 are the same in composition and optical properties. Optically homogeneous materials are disclosed in, e.g., United States Patents 6,120,839, 6,103,860,

6,084,086, 6,080,833, 6,019,472, 5,970,746, 5,914,760, 5,841,572, 5,808,784, 5,754,290, and the like.

The substrate 12 depicted in Figure 1 preferably consists of material which has a coefficient of thermal expansion of from about 2×10^{-5} to -1×10^{-6} per degree centigrade. It is preferred that the coefficient of thermal expansion to be about 6×10^{-7} to about -6×10^{-7} per degree centigrade.

One may use a variety of transmissive materials known to those skilled in the art. Thus, e.g., one may use optical glass, plastics, glass-ceramic, crystalline materials, and the like. Suitable materials include, e.g., "CLEARCERAM-Z" (a glass-ceramic material made by the Ohara Incorporated of Japan), ULE (a ultra-low expansion glass sold by the Corning Company of Corning, New York), fused silica, BK7 optical glass, plexiglass, crystalline quartz, silicon, etc. ULE glass is made by doping fused silica with titanium and, thus, has essentially the same optical properties as fused silica. ULE glass is referred to in, e.g., United States Patents 6,048,652, 6,005,995, 5,970,082, 5,965,879, 5,831,780, 5,829,445, 5,755,850, 5,408,362, 5,358,776, 5,356,662, and the like.

The substrate 12 preferably has a refractive index of from about 1.4 to about 4.0. In one embodiment, the refractive index of substrate 12 is from about 1.43 to about 1.7.

The thickness 16 of substrate 12 is generally from about 0.5 millimeters to about 100 millimeters and, preferably, from about 2 to about 20 millimeters. The thickness 18 of the grating forming layer 14 generally ranges from about 1 micron to about 5 microns. The ratio of thickness 16 to thickness 18 is generally at least about 500/1 and, more preferably, at least about 1,000/1.

Figure 2 is an exploded partial sectional view of area 20 of Figure 1, depicting the surface-relief diffraction grating 15 in greater detail. Grating 15 is comprised of a base 22 integrally connected to upstanding periodically spaced grating lines 24. The periodically spaced grating grooves 26 are disposed between adjacent grating lines 24.

In one embodiment, the surface-relief grating 15 is formed in the grating forming layer 14 by a photographic process, such as holography. In another embodiment, the surface-relief grating 15 is formed in the grating forming layer 14 by replication means. In another embodiment, the surface-relief grating 15 is etched into the substrate 12 material using either

chemical or ion beam milling techniques. Normally a grating formed in a photoresist material by photographic means serves as the mask for these etching techniques.

In one preferred embodiment, the grating forming layer 14 consists essentially of material with an index of refraction of from about 1.4 to about 1.8 and, more preferably, from about 1.43 to about 1.55.

In the embodiment depicted in Figure 2, the grating 15 has a substantially sinusoidal shape. In another embodiment, not shown, grating 15 has a substantially rectangular shape. In another embodiment, the gratings 15 may have a substantially triangular shape.

Sinusoidal diffraction gratings are disclosed in United States Patents 6,026,053, 5,757,544, 5,755,501, 5,742,262, 5,737,042, 5,696,628, 5,341,213, 4,842,969, 4,729,640, 4,062,628, and 3,961,836.

In one embodiment, the grating is formed from a photoresist material which, after being heat-treated, becomes a substantially dry solid material. It is preferred to use a positive photoresist material. Positive photoresist materials are well known to those skilled in the art and are disclosed, e.g., in United States Patents 6,094,410, 6,094,305, 6,051,348, 6,027,595, 6,005,838, 5,991,078, 5,965,323, 5,936,254, 5,910,864, 5,907,436, 5,838,853, and the like. In one embodiment, the positive photoresist material used is Shipley S1813 Photo Resist (manufactured by The Shipley Company of 455 Forest Street, Marlboro, Mass.). This positive photoresist material is comprised of from 71 to 76 parts of electronic grade propylene glycol monomethyl ether acetate, from about 10 to about 20 parts of mixed cresol novolak resin, from about 0.01 to about 1 parts of fluoroaliphatic polymer esters, from about 1 to about 10 parts of diazo photoactive compound, and from about 0.01 to about 0.99 parts of cresol.

The Shipley S1813 Photo Resist is believed to belong to a class of diazonaphthoquinone (DNQ)-novolak positive photoresists; see, e.g., pages 431-511 of James R. Sheats et al.'s "Microlithography Science and Technology (Marcel Dekker, Inc., New York, 1998) and, in particular, an article commencing at page 429 of this book by Takumi Ueno on "Chemistry of Photoresist Materials."

Referring again to Figure 2, it will be seen that grating forming layer 14 is comprised of a base layer 22 which, preferably, is at least about 0.25 microns thick, as well as the actual surface-relief grating 15.

The surface-relief grating 15 depicted in Figure 2 is preferably periodic, that is substantially the same shape is repeated. In the preferred embodiment depicted in Figure 2, the grating has a groove frequency ("G") of from about 400 to about 1,100 grating lines per linear millimeter. In one embodiment, there are from about 500 to about 900 grating lines per linear millimeter.

The distance between adjacent grating line 24 peaks (or valleys) is referred to as the grating line spacing D and is shown in Figure 2. D is the reciprocal of G, the groove frequency and, thus, ranges from about 0.91 to about 2.5 microns and, preferably, from about 1.11 to about 2.0 microns.

The peak height of the lines 24, "h," as shown in Figure 2, is the maximum distance from the trough to the peak of the grating lines 24. In general, h ranges in height from about 0.5 microns to about 5 microns.

The ratio of h to D, which is also referred to as the grating aspect ratio, and in the preferred transmission grating embodiment has a value of about 1.3 to about 2.0. In another embodiment in which a surface-relief reflection grating is used, the h/D ratio is preferably from about 0.3 to about 0.4 for the reflection grating element.

Referring again to Figure 1, the grating 15 is a plane diffraction grating having parallel, equidistantly spaced grating lines which reside on a flat surface. When one looks down onto the grating surface of the grating element 10, he will see a multiplicity of parallel grating groove lines spaced equidistantly from each other. One of the properties of a plane diffraction grating is that it does not introduce optical power into the diffracted beam, i.e., a collimated incident beam is diffracted as a collimated beam.

The grating 15 is believed to be substantially more durable, when tested by a specified test, than are comparable prior art photoresist surface-relief diffraction gratings. The test used to evaluate the durability of grating 15 is set forth in Bellcore publication GR-1221-CORE, issue 2, January, 1999, entitled "Generic Reliability Assurance Requirements for Passive Optical Components." At page 6-4 of this publication, a "High Temperature Storage Test (Damp Heat)" is described. This test requires that the item tested, when subjected to a temperature of 85 degrees centigrade and a relative humidity of 85 percent, have less than 0.5 decibel optical insertion loss variation after being tested for at least 500 hours. The

functionality of the item under test is periodically evaluated. A change of 0.1 decibel in optical insertion loss corresponds to a change of 2.27 percent in the optical performance of the item while a 0.5 decibel change corresponds to a 10.875 percent change in the optical performance of the item.

The preferred diffraction grating element 10 of this invention meets the aforementioned Bellcore test requirements for at least about 1,700 hours.

One preferred process for preparing the grating element 10 of this invention is disclosed in Figure 3. Referring to Figure 3, in step 50 photoresist is applied to the top surface of a substrate. The substrate preferably is either rectangular or circular in shape and, most preferably, is made from the ULE glass material described elsewhere in this specification. In one preferred embodiment, the substrate is about 3.5 millimeters thick.

The preferred photoresist material is spread over the top surface of the substrate to a uniform thickness, preferably by a spin coating method in which the substrate is rotated at a speed of from about 2,000 to about 4,000 revolutions per minute and the photoresist is spread and dried by centrifugal force. In one embodiment, the photoresist is applied to a thickness of about 3 microns.

Thereafter, in step 52 of the process, the coated substrate is heated to vaporize any remaining solvent in the coating. It is preferred to place the substrate onto a hot plate preheated to a temperature of about 110 degrees centigrade and to so heat the coated substrate for a period of from about 2 to about 10 minutes.

Thereafter, in step 54, the substrate is removed from the hot plate and allowed to cool under ambient conditions for at least about 5 hours.

Thereafter, in step 56, the substrate is exposed to a holographically generated optical interference pattern. Such optical interference pattern is preferably produced by two interfering collimated laser beams which are derived from the same helium cadmium laser operating at a wavelength of 442 nanometers. The angle subtended by the interfering beams determines the period of the interference pattern and, thus, the period of the final diffraction grating. Reference may be had to many different United States patents which disclose surface-relief holograms, including, e.g., United States Patents 6,160,668, 6,157,474, 6,067,214, 6,049,434, 6,017,657, 5,986,838, 5,948,199, 5,917,562, 5,896,483, 5,889,612, 5,961,990, 5,856,048, 5,838,466, 5,790,242, 5,786,910, 5,757,523, 5,757,521, 5,756,981,

5,748,828, 5,742,411, 5,712,731, 5,691,831, 5,691,830, and the like.

Thereafter, in step 58, the exposed latent image in the photoresist layer is developed by submerging the exposed photoresist in developer.

One may use conventional developing solutions such as, e.g., one or more of the photoresist developers disclosed in United States Patents 6,087,655, 6,067,154, 5,881,083, 5,805,755, 5,607,800, 5,521,030, 5,113,286, 4,826,291, 4,804,241, 4,725,137, 4,617,252, 4,589,972, 4,566,889, 4,505,223, 4,469,544, 4,236,098, 4,204,866, 4,157,220, 3,945,825, 3,944,420, and the like.

In one embodiment, the photoresist developer used is Shipley's "Microposit 303A Developer." This developer is believed to be a sodium hydroxide solution at a pH of about 14.

After the photoresist has been exposed to the developer, it is rinsed with filtered deionized water and spun dry in step 60 at a speed of about 500 revolutions per minute for about 1 minute until the grating surface appears dry.

The grating is then inspected, using a laser beam, to determine its diffraction efficiency. This diffraction efficiency information may be used to adjust either the exposure time and/or development time so that the process conditions for subsequently produced gratings may be adjusted and controlled.

The steps 62 et seq. describe critical post-exposure/development steps for insuring that the ultimate grating produced has improved durability properties, as measured by the aforementioned Bellcore test.

In the preferred process of this invention, when the photoresist is sequentially subjected to the ultraviolet light exposure and thereafter subjected to high temperature, not only is a durable grating produced, not only does the treated photoresist material not become dark, but the treated photoresist material becomes clearer and optically more desirable.

In step 62 of the process, the photoresist surface of the developed diffraction grating is at ambient room temperature and pressure conditions directly exposed to a lamp producing ultraviolet light in the spectrum range of from about 200 to about 320 nanometers, which is often referred to as deep ultraviolet (DUV) radiation. For example, one may use one or more of the lamps disclosed in United States Patents 4,389,482, 4,344,008, 4,312,934, 4,299,911,

and 4,049,457, the entire disclosure of each of which is hereby incorporated by reference into this specification.

Unlike prior processes, there is no intermediate material, except air, positioned between the DUV light source and the photoresist. The distance between the DUV lamp and the unprotected photoresist surface is generally from about 6 to about 10 inches. One may use, e.g., conventional germicidal lamps for this purpose such as, e.g., Germicidal Lamp FG15T8. The photoresist surface is exposed to such ultraviolet light for about 10 minutes.

The Germicidal Lamp FG15T8 is 18 inches long, operates at 0.3 amperes and 56 volts, has a nominal lamp wattage of 15 watts, provides 3.5 watts of ultraviolet radiation at 253.7 nanometers, and has an average life of 8,000 hours.

Exposure of the photoresist grating forming layer to the DUV light source at ambient room temperature and pressure conditions bleaches the photoresist layer and, thereby changes the color of the photoresist layer from a yellow color to a substantially optically clear color having no visible observable color tint. This substantially optically clear color is sometimes referred to as water white. The photoresist layer stays substantially optically clear not only after being heated in step 64 of the process but also after being tested for about 1,000 hours at the previously described Bellcore test conditions, whether the grating surface is uncovered or encapsulated as illustrated in Figure 9 of this specification. It is noticed that an uncovered grating develops a very light yellow tint color after about 1,700 hours of testing at the Bellcore test conditions. This yellow tint color does not appear to affect the diffraction efficiency performance of the grating when tested at laser wavelength of 633 nanometers.

In step 64 of the process, the exposed photoresist surface is then heat treated by being heated in a relatively dry oven to a temperature of from about 110 to about 150 degrees centigrade, preferably for at least about 30 minutes. It is preferred that the photoresist surface be placed into a preheated oven at the desired temperature of from about 110 to about 150 degrees centigrade.

For surface-relief transmission grating elements that undergo steps 62 and 64 of the process presented in Figure 3, the grating elements after being tested at the aforementioned Bellcore test conditions of 85 degrees centigrade and 85 percent relative humidity for at least 1,000 hours, have optical performance as measured by their diffraction efficiency values for light of 633 nanometers and S optical polarization that is within 6 percent of the optical

performance they had prior to being tested at the Bellcore test conditions. Therefore, grating elements undergoing steps 62 and 64 of the process pass the aforementioned Bellcore test conditions since this Bellcore test deems that an item passes these test conditions if its optical performance does not change by more than 0.5 decibels (10.87 percent) after being tested for 500 hours at these test conditions.

The grating fabrication processing steps 50 through 64 of Figure 3 can be utilized to produce both surface-relief transmission gratings and surface-relief reflection gratings. Surface relief transmission gratings fabricated with these processing steps are exposed and developed so that the finished grating has a grating aspect ratio in the range of about 1.3 to about 2.0 while surface-relief reflection gratings fabricated with these processing steps are exposed and developed so that the finished grating has a grating aspect ratio in the range of about 0.3 to about 0.4. After step 64 of the process, the grating surface of a reflection grating is coated with a reflecting metal film, such as gold or aluminum. The reflective metal film is usually applied to the grating surface using either evaporation or electronic beam sputtering techniques that are performed in a vacuum chamber.

The finished diffraction grating has certain unique properties. It has the durability property and substantially optically clear color property that are described elsewhere in this specification. It also preferably has a diffraction efficiency of greater than 70 percent for optical wavelengths in the 1280 to 1620 nanometer spectrum region that fiber-optic communication systems use. It also preferably has essentially equal diffraction efficiency values for S and P polarized optical components, that is, the S and P polarizations have diffraction efficiency values within about 5 percent of each other.

Figure 4 presents measured diffraction efficiency data for a sinusoidal surface-relief transmission grating formed in photoresist. This data is presented as a function of λ/D which is the ratio of the optical wavelength, λ, of the beam incident on the grating to the grating line spacing D, and for the Littrow diffraction condition, that is $\theta_i = \theta_d$. The definition used to calculate the grating diffraction efficiency data values in Figure 4, and used in this specification in reference to diffraction efficiency, is that the diffraction efficiency of a grating element is the ratio of the intensity of the first order diffracted beam divided by the intensity of the beam incident to the grating diffracting surface for either the S or P polarized optical component of the beam. This definition of diffraction efficiency does not account for

optical insertion losses in the grating element due to reflection losses at the substrate non-grating surface or by optical absorption with the substrate material. These substrate related optical insertion losses can be minimized by using antireflection coatings on the non-grating substrate surfaces and/or by using substrate materials having low optical absorption for the wavelength spectrum used with the grating element. The measured data points are shown on the graph in Figure 4 as open circles for both polarization components, while the drawn curves represent the best fix to this data. In this specification, when discussing the performance of a transmission diffraction grating, we will use the American polarization convention, that is, S polarized light has its electric field parallel to the grating lines while P polarized light has its electric field perpendicular to the grating lines. To achieve the high diffraction efficiency values presented in Figure 4, the surface-relief transmission grating must have a deep groove profile shape, that is, the grating aspect ratio must be between about 1.3 and 2.0.

When the incident and diffracted optical beams to a surface-relief transmission grating have substantially equal angles with respect to the normal to the grating surface the S polarized optical component has a diffraction efficiency of at least 70 percent for λ/D ratios of from about 0.8 to about 2.0 while the P polarized optical component has a diffraction efficiency of at least 70 percent for λ/D ratios of from about 0.8 to about 1.2 and has a value that decreases from at least 70 percent when the λ/D ratio is about 1.2 to a value of less than 10 percent when the λ/D ratio is about 1.43 to about 2.0.

Examination of Figure 4 reveals that essentially equal diffraction efficiency values for both S and P polarization optical components can be achieved with a transmission sinusoidal surface-relief grating having a λ/D range of about 0.8 to approximately 1.2. Also, as the Figure 4 data shows, surface-relief transmission gratings can achieve diffraction efficiency values of greater than 90 percent for both S and P polarizations for the 0.8 to 1.2 λ/D ratio range and do not exhibit the anomalies in diffraction efficiency performance as a function of λ/D ratio that are observed with reflecting surface-relief gratings.

In one embodiment, it is preferred that grating 15 be operated so that the incident and diffracted beams have substantially equal angles with respect to the normal to the grating surface, that is, being within about 15 degrees of the Littrow diffraction condition.

In one embodiment, the diffraction grating 15 is operated so that the diffraction efficiency values for both the S and P polarized optical components are within 10 percent of each other, which corresponds to operating a surface-relief transmission grating with a λ/D ratio of from about 0.8 to about 1.2.

Using a surface-relief transmission grating element at a λ/D ratio value higher than about 1.2 results in the grating having different diffraction efficiency values for the S and P polarization components (see Figure 4). Using diffraction grating-based devices that have different diffraction efficiency values for the S and P polarizations may significantly increase the polarization dependent noise level of fiber-optic communications systems incorporating the devices. In a grating-based device using a surface-relief transmission grating having a λ/D value greater than about 1.2, this polarization dependent noise problem can be ameliorated by incorporating polarization controlling optical elements into the device so that the device achieves essentially equal radiometric throughput efficiency values for the S and P polarized optical components. Radiometric throughput efficiency for a component, device or a system is defined as the ratio of the intensity of the optical beam exiting the component, device or system divided by the intensity of the optical beam incident to the component, device, or system and is usually measured for each optical polarization component.

The polarization dependent noise level of a fiber-optic communication system is increased whenever a device having greater than about 5 percent difference between its radiometric throughput efficiency values for S and P polarized optical components is incorporated into the system. This increase in polarization dependent noise level occurs because the optical beams propagating in fiber-optic communication systems have no defined polarization direction and continually change polarization direction as a function of time.

Because the polarization dependent noise level of a device used in a fiber-optic communication system is determined by the difference between its radiometric throughput efficiency values for S and P polarized optical components, the preferred grating-based device embodiments in this specification are operated to have radiometric throughput efficiency values for S and P polarizations that are equal to within about 5 percent of each other. This is accomplished in some of the preferred grating-based device embodiments by using surface-relief diffraction grating elements that have essentially equal diffraction efficiency values for S and P optical polarizations. While not specifically stated for each of

the preferred grating-based device embodiments in this specification, the other optical components used in these devices, such as fibers, lenses, mirror reflecting surfaces, non-grating transmitting surfaces, etc., incorporate thin film optical coatings that not only improve the radiometric efficiency performance of the component, and therefore the device, but also ensure that these components have radiometric throughput efficiency values for S and P optical polarization components that are equal to within about 5 percent of each other. If the grating element used in the device has a diffraction efficiency difference of up to about 10 percent between the S and P polarized optical components, its radiometric throughput inefficiency difference for S and P polarizations can be compensated for by incorporating optical components into the device that have the opposite radiometric throughput inefficiency difference with regard to the S and P polarization components. When the grating element used in the device has a difference of greater than about 15 percent between the S and P polarized optical components, the device incorporates polarization controlling optical elements that enable the device to achieve radiometric throughput efficiency values for S and P polarizations that are equal to within about 5 percent of each other.

The grating-based devices described in this specification are configured so that the optical components of the device function as an optically integrated assembly so that the device achieves radiometric throughput efficiency values for S and P polarized optical components that are equal to within about 5 percent of each other.

Figure 5 schematically illustrates a preferred embodiment in which the surface-relief transmission grating element 10 is incorporated into a spectrophotometer device 80 used as part of an on-line wavelength channel monitoring system capable of obtaining information about the optical power, wavelength and optical-signal-to-noise ratio of each wavelength signal channel in a wavelength-division multiplexing ("WDM") fiber-optic communication system.

As depicted in Figure 5, input optical wavelength channel signal information is delivered to device 80 by transmission fiber 82. Input transmission fibers are well known to those skilled in the art and are disclosed, e.g., in United States Patents 6,151,145, 5,798,855, 5,790,285, 5,745,613, 5,532,864, 5,452,124, 5,377,035, and the like.

The input transmission fiber 82 to the spectrophotometer monitor device 80 contains λ_1, λ_2, and λ_3 wavelength channel signals which exit from the end of the fiber as a diverging

optical ray bundle 84. The collimating lens assembly 86 receives the ray bundle 84 diverging from the end of the input fiber 82 and converts it into a collimated beam 88 which is incident on the transmission grating element 10. After being diffracted by element 10 the incident beam 88 is separated into λ_1, λ_2, and λ_3 wavelength channel beams 90 which propagate at slight angles with respect to each other in the plane which is perpendicular to the diffraction grating lines of element 10, which Figure 5 resides in. The focusing lens assembly 92 receives the angularly separated collimated λ_1, λ_2, and λ_3 wavelength beams 90 from the grating element 10 and focuses these beams onto the surface of the photodetector linear array element 94.

The spatially separated focused wavelength channel beams 96 are incident on different photosensitive elements (not shown) in the photodetector array 94 and, thereby, generate an independent electrical signal 98 for each wavelength channel beam. The amplitude of each electrical signal 98 is proportional to the average light intensity of the wavelength channel beam incident on the photodetector element generating that signal. While only three wavelength channel beams are shown being used with the monitoring device 80 of Figure 5, it is evident that device 80 can be used with many more wavelength channel beams. An InGaAs (indium gallium arsenide) photodetector array will normally be incorporated into wavelength monitoring devices used for communication systems operating in the 1280 to 1620 nanometers spectrum region. Commercial InGaAs photodetector arrays are available with 128, 256, and 512 photodetector elements having either 25 or 50 micron spacing between element centers. InGaAs photodetector fibers are well known to those skilled in the art and are disclosed, e.g., in United States Patents 5,838,470, 5,714,773, 5,428,635, 5,386,128, 5,055,894, 4,879,250, and the like.

In the device 80 of Figure 5 the optical components are enclosed within a housing 100, which protects the optical components from contaminants. It is preferred that the housing 100 be comprised of components which do not adversely affect the performance of the optical components over the 70 degree operating temperature range specified for fiber-optic devices.

It is desired to increase the dispersion of the grating element 10 used in the device 80 while still achieving essentially equal diffraction efficiency values for the S and P polarization components of the optical beam. To this end, one can use a λ/D ratio of about

1.2 and still achieve essentially equal diffraction efficiency values for the S and P polarized optical components and, one can increase the dispersion power of grating element 10 by increasing the diffraction angle θ_d used in the device.

The required focal length of the focusing lens assembly 92 used in the Figure 5 monitor device 80 can be calculated. For example, if it is assumed that the spatially separated focused wavelength channel beams 96 in device 80 are incident on adjacent photosensitive elements in the photodetector array 94 and that these elements have a 50 micron spacing between element centers, that the device 80 incorporates a surface-relief transmission grating element 10 having a λ/D ratio of 1.0 for an optical wavelength of 1550 nanometers, and that $\theta_i = \theta_d = 30$ degrees for a wavelength of 1550 nanometers, then the focusing lens assembly 92 used in device 80 must have a focal length of 83.9 millimeters when used with a WDM fiber-optic system having 0.8 nanometers (100 GigaHertz) spacing between wavelength channels. One could reduce the focal length for this WDM system requirement down to approximately 60 millimeters by using a surface-relief transmission grating element 10 having a λ/D ratio of 1.15 that operated with $\theta_i = 26.3°$ and $\theta_d = 45°$. The focal length of the focusing lens assemblies used in spectrophotometer units used to monitor the performance of WDM fiber-optic systems having 40 or more channels cannot be made much shorter than 60 millimeters, since the lens assemblies must provide good imaging performance across a photodetector array surface area that is 2 millimeters or more in length.

One may physically shorten the Figure 5 monitoring device 80 by positioning a beam fold mirror element after the transmission grating element 10 in device 80 such that the mirror reflects the diffracted beams essentially parallel to the input beam path 88, as depicted in Figure 6. The wavelength channel monitoring device 120 in Figure 6 functions exactly as described for the monitoring device 80 in Figure 5. In addition to incorporating beam fold mirror element 122, the device 120 has been modified relative to the device 80 in Figure 5 in several ways. Only a single wavelength beam 90 is depicted in device 120. The focal length of the focusing lens assembly 92 in device 120 is significantly longer than the focal length for the collimating lens assembly 86 used in this device. The collimating and focusing lens assemblies in device 120 are depicted as air spaced doublets vs. the air spaced triplet lens assemblies depicted in device 80 of Figure 5. The transmission grating element 10 in device 120 is depicted as functioning with $\theta_i = 28$ degrees and $\theta_d = 45$ degrees, while the

transmission grating element 10 in device 80 of Figure 5 is depicted as functioning with $\theta_i = \theta_d = 30$ degrees. Device 120 incorporates an internal light baffle element 124 to shield the photodetector linear array element 94 from any back-scattered light originating in the input beam path prior to and including the grating element 10. The size of the photodetector linear array element 94 in Figure 6 is depicted considerably larger than the corresponding element in Figure 5 to more accurately reflect the dimensions of current commercially available InGaAs linear array elements.

Because the collimating and focusing lens functions in the Figures 5 and 6 wavelength monitoring devices are separate, one can optimize the lenses used for these imaging functions and thereby potentially improve upon the cost/performance ratio of the device. While the collimating and focusing lens assemblies in Figures 5 and 6 are depicted as composed of either three or two conventional singlet lens elements, one could use fewer conventional spherical lens elements, and/or lens elements having aspheric surfaces and/or gradient index based lens elements, such as a SELFOC lens (sold by NSG America, Inc. of Somerset, New Jersey) for these lens assemblies. One could also use a combination of lens and mirror elements, or just mirror elements, to construct the collimating and focusing lens assemblies depicted in Figures 5 and 6. The collimating lens assemblies used in the Figures 5 and 6 devices can have a simpler lens assembly configuration than used for the focusing lens assemblies in these devices since the collimating lens function only on axis.

Appropriate lens assembly combinations will be apparent to those skilled in the art, as described in the following patents. Typical collimating lens assemblies are disclosed in United States Patents 6,279,464, 6,169,630, 6,137,933, 6,028,706, 6,011,885, 6,011,884, 6,008,920, 4,852,079, 4,405,199, and the like. Focusing lens assemblies are disclosed, e.g., in United States Patents 6,167,174, 6,097,860, 6,097,025, 6,094,261, 6,075,592, 5,999,672, 5,793,912, 5,450,510, 5,450,223, 5,440,669, 5,026,131, 4,479,697, and the like.

The focusing lens assembly 92 in device 120 of Figure 6 is depicted as having a focal length that is in the range of 2 to 3 times longer than the focal length used for the collimating lens assembly 86 used in this device. This 2 to 3 difference in focal lengths between these lens assemblies can be used because the InGaAs photodetector linear arrays 94 used in the monitoring devices 80/120 have an element cell size in the range of 25 to 50 microns, while the input fibers 82 used in these devices have a core diameter in the range of 8

to 9 microns. Because of the 3 to 1 or greater ratio between input fiber core diameter and photosensitive element cell size for the Figures 5 and 6 monitoring devices, one can use a collimating lens assembly in these devices having a focal length which is only approximately one-third of the focal length used for the focusing lens assembly incorporated in these devices and thereby optimize the numerical aperture (NA) imaging performance for each lens assembly, which should improve the cost/performance ratio of the device.

While the inclusion of the beam fold mirror element 122 in device 120 of Figure 6 reduces the physical size of the wavelength monitoring device relative to the embodiment illustrated in Figure 5, it does not change the wavelength dispersion properties of the device relative to that achieved with the Figure 5 device. The beam fold mirror element 122 can be configured so that it not only reduces the size of the device but also effectively doubles the wavelength dispersion power of the transmission grating element 10 used in the device.

Figure 7 schematically illustrates how a beam fold mirror element 122 can be utilized so that the incident beam 84 makes a dual pass through the surface-relief transmission grating element 10 and thereby doubles the wavelength dispersion power of the grating element 10. The incident beam 84 to the transmission grating element 10 in device 130 of Figure 7 contains λ_1 and λ_2 wavelength components. After the incident beam is diffracted by the grating element 10, these optical wavelength components are angularly separated by $\Delta\theta$. The mirror element 122 in device 130 is angularly orientated so that the λ_1 wavelength beam 132 is retroreflected back on itself. Because the grating element 10 functions in a reversible manner, the grating element 10 rediffracts the retroreflected λ_1 wavelength 132 beam back along the direction of the incident beam 84 as beam134. The dual pass transmission grating arrangement of device 130 mimics a reflection grating element operating at the Littrow condition for the λ_1 wavelength beam, since this beam is retrodiffracted back on itself. After reflecting from the mirror element 122, the λ_2 wavelength beam 136 in device 130 propagates back to the grating element 10 where, due to its angle of incidence, the λ_2 wavelength beam 136 is rediffracted from the grating element 10 with an angle equal to approximately $2\Delta\theta$ relative to the propagating direction of the retrodiffracted λ_1 wavelength beam 134.

In effect, the grating element 10 and mirror element 122 combination in device 130 of Figure 7 doubles the λ/D value of the grating element 10. By using the grating/mirror combination in device 130, surface-relief transmission grating-based devices can be constructed with effective λ/D grating values of 1.6 to 2.4 while achieving essentially equal diffraction efficiency values for S and P polarized optical components. The high wavelength dispersion power provided by these dual pass transmission grating-based devices provides significant advantages when these devices are used in WDM fiber-optic communication systems.

The grating/mirror combination in device 130 of Figure 7 achieves the effective doubling of the λ/D value of grating element 10 by cascading the grating dispersion power of grating element 10, similar to the narrowing of the spectrum band-pass width of an interference wavelength selection filter device by the cascading of filter elements. This cascading of the grating dispersion power does not effect the wavelength filter function of the grating-based devices incorporating this cascaded grating arrangement, since the wavelength filter function of these grating-based devices is determined by the physical dimensions of the output array structures used in those devices. The only significant negative associated with using this cascaded grating arrangement is a decrease in device throughput radiometric efficiency associated with the optical power loss due to the beam being diffracted twice by the grating element. It is estimated that greater than 80 percent radiometric throughput efficiency can be achieved for both S and P polarized beam components propagating twice through a surface-relief transmission grating element having a λ/D ratio value in the range of 0.8 to 1.2 for optical wavelengths in the 1280 to 1620 nanometers spectrum range.

Referring again to Figure 7, one can change the wavelength of the beam 134 retrodiffracted back on itself, and thus change the wavelength tuning parameters of the device 130, by rotating the mirror element 122 in the direction of arrow 138 and/or arrow 140 by conventional means. This wavelength tuning property is well known and is used in conventional double-pass mirror-reflection grating-based spectrophotometers, as discussed in an article by Ghislain Levesque in the June, 2000 issue of Photonics Spectra (see Figure 5 on page 110).

The dual pass transmission grating arrangement in Figure 7 is accomplished by using separately a grating element 10 and mirror element 122. By comparison, and as illustrated in

Figure 8, a dual pass transmission grating device 150 can be fabricated using a single transmission glass block element 152 that incorporates a surface-relief transmission grating 15 and a reflecting mirror surface 154. The device 150 functions as described for the device 130 in Figure 7. As depicted in Figure 8, a single wavelength beam 84 is incident on the dual pass grating device 150 at the Littrow diffraction condition for the dual pass arrangement depicted in device 150 and is retrodiffracted back along the incident beam path 84 as beam 134. As depicted in Figure 8, the non-optical transmitting and reflecting surfaces of the glass block 152 have been coated with an optical absorption coating 156 that is designed to absorb the nondiffracted zeroth order beam energy and other scattered light which may occur within the glass block element 152. Optical absorption coatings are well known to those skilled in the art and are disclosed, e.g., in United States Patents 6,075,635, 5,893,364, 5,633,494, and the like.

Figure 9 schematically illustrates how the dual pass transmission grating device 150 of Figure 8 can be fabricated using a surface-relief transmission grating element 10 that is attached to the input optical transmitting surface of glass block element 152 incorporating reflecting mirror surface 154. The device 160 in Figure 9 functions as described for the device 130 in Figure 7. As depicted in Figure 9 a single collimated wavelength beam 162 is incident on the dual pass grating device 160 at the Littrow diffraction condition for the dual pass arrangement depicted in device 160 and is retrodiffracted back along the incident beam path 162 as beam 166.

As depicted in Figure 9, the device 160 is fabricated so that the grating surface 15 of the grating element 10 is encapsulated between the substrate 12 of grating element 10 and the input optical transmitting surface to the glass block element 152. A sealing element 168, such as epoxy, is used in device 160 to encapsulate the air gap layer 170 that exists between the surface-relief transmission grating surface 15 and the input optical transmitting surface of the glass block element 152. The main function of the sealing element 168 is to prevent contaminants, liquids or solvent vapors that could damage the grating surface from entering the air gap layer 170. The encapsulated grating surface configuration of device 160 also protects the grating surface from being damaged due to handling and cleaning of the grating element. The input optical transmitting surfaces of both the grating substrate 12 and the glass block 152 are antireflection coated to minimize optical reflection losses at these surfaces. As

depicted in Figure 9, the non-optical transmitting and reflecting surfaces of the glass block 152 have been coated with an optical absorption coating 156 that is designed to absorb the nondiffracted zeroth order beam energy and other scattered light which may occur within the glass block element 152. The glass block elements depicted in Figures 8 and 9 can be made longer or shorter than what is depicted in these figures.

Schematic top, side and isometric views in Figures 10A, 10B and 10C, respectively, illustrate how the dual pass grating element 150 of Figure 8 can be incorporated into demultiplexer (Demux) device 180 used in fiber-optic WDM systems. The input transmission fiber 182 to the Demux device 180 contains λ_1, λ_2, and λ_3 wavelength channel signals which when exiting from the end of the fiber 182 form a diverging optical ray bundle 186 having a cone angle determined by the numerical aperture (NA) of the input fiber 182. The end of the fiber 182 is supported and positioned by holder 183 at the focal plane of the collimating/focusing lens assembly 87. The collimating/focusing lens assembly 87 receives the ray bundle 186 diverging from the end of the input fiber 182 and converts it into a collimated beam 188 which is incident on the dual pass grating element 150. As depicted in Figure 10A, the incident beam after being diffracted by the dual pass grating element 150 is separated into λ_1, λ_2, and λ_3 beams 190 which propagate at slight angles with respect to each other in the plane perpendicular to the diffraction grating lines, which Figure 10A resides in. In the plane parallel to the grating lines, which Figure 10B resides in, the dual pass grating element 150 functions like a mirror in that the incident beam 188 and the different diffracted wavelength beams 190 have essentially the same angle with respect to the normal to the grating surface 15 in this plane.

As depicted in Figures 10A and 10B, the collimating/focusing lens assembly 87 receives the collimated diffracted λ_1, λ_2, and λ_3 wavelength beams 190 from the dual pass grating element 150 and focuses these beams onto the surface of the output fiber array 184. As indicated in Figure 10A, and more clearly in Figure 10C, the output fiber array 184 consists of individual fibers 192, 194, and 196 arranged in a row structure, the orientation of that row being parallel to the plane that is perpendicular to the grating lines. In the plane of the row the fibers are essentially evenly spaced by a distance W that is equal to the product of the focal length of the collimating/focusing lens assembly 87 and the diffracted angular separation between wavelength beams 190. The output fiber array 184 is spatially positioned

so that each of the spatially separated focused wavelength channel beams 191 is incident on its corresponding output fiber in the array 184. Essentially all of the light incident on the core are of an output fiber in the array 184 is coupled into the fiber and transmitted to a separate photodetector device (not shown) that provides an electrical data signal corresponding to the information transmitted on that wavelength channel.

In the preferred embodiment depicted in Figures 10A, 10B and 10C, the optical components are enclosed within a housing 100, which protects the optical components from contaminants. It is preferred that the housing 100 be comprised of components which do not adversely affect the performance of the optical components over the 70 degree operating temperature range specified for fiber-optic devices.

The Demux device depicted in Figures 10A, 10B and 10C functions in a reversible manner, that is, the device can be used to optically combine different wavelength channels onto a single output fiber, thereby functioning as a multiplexer (Mux) device.

The grating-based device illustrated in Figures 10A, 10B and 10C can be used to simultaneously Mux and Demux wavelength channels and thereby be used to construct a bi-directional fiber-optic network system which provides dramatic cost savings in local and metro area networks not incorporating in-line optical amplifiers. One method for achieving this bi-directional operation is by having adjacent wavelength channels be transmitted in opposite directions. This adjacent counter-propagating wavelength channel arrangement minimizes cross-take between both co-propagating and counter- propagating wavelength channels and still enables the input/output fiber-optic array holder to be constructed with essentially equal spacing between fibers.

Schematic top, side and isometric views are, respectively, presented in Figures 11A, 11B and 11C of an on-line wavelength channel signal monitoring device 200 that utilizes dual pass grating element 150 of Figure 8. Comparison of the device of Figures 10A, 10B and 10C with the device of Figures 11A, 11B and 11C reveals that the only significant difference between the Demux device 180 and the spectrophotometric monitoring device 200 is that the output fiber array 184 of the Demux device 180 is replaced in the monitoring device 200 by a photodetector linear array 202 that is positioned at the focal plane of the collimating/focusing lens assembly 87. The monitoring device 200 functions exactly as described for the Demux device 180 with the exception that in the monitoring device 200 the

spatially separated focused wavelength channel beams 191 are incident on different photosensitive elements in the photodetector array 202 and, thereby, generate an independent electrical signal 204 for each wavelength channel. The amplitude of each electrical signal is proportional to the average light intensity of the wavelength channel beam incident on the photodetector element generating that signal. While only three wavelength channels are shown being used with the monitoring device 200 illustrated in Figures 11A, 11B and 11C, it is evident that this device can be used with many more wavelength channels. An InGaAs photodetector array will normally be incorporated into monitoring devices used for communication systems operating in the 1280 to 1620 nanometer spectrum region. Commercial InGaAs photodetector arrays are available with 128, 256, and 512 photodetector elements having either 25 or 50 micron spacing between element centers.

Comparison of the wavelength monitoring device depicted in Figures 11A, 11B, and 11C with the corresponding devices depicted in Figures 5 and 6 shows that, by using a dual pass transmission grating arrangement versus a single pass grating arrangement, one has spatially and functionally combined the collimating and focusing lens assemblies, significantly decreased the spatial separation between the input and output image planes of the device, and decreased the size of the device. It should be noted that current commercially available InGaAs photodetector arrays used in these devices have overall package sizes in the range of 63 millimeters by 25 millimeters, which is significantly larger than what is depicted in Figures 11A, 11B and 11C when compared to the other components depicted in these figures. Because of the relatively large size of current InGaAs photodetector arrays, there has to be a significantly greater distance between the array unit and input fiber element in Figure 11B, which increases the requirements on the performance of the collimating/focusing lens assembly used in this device.

By separating the collimating and focusing lens functions in the Figures 5 and 6 monitoring devices, one can optimize the lenses used for these imaging functions and thereby potentially improve upon the cost/performance ratio of the device, as previously described.

One can further increase the wavelength dispersion power of the dual pass grating arrangements of Figures 7, 8 and 9 by incorporating a beam expanding prism element into these devices as illustrated in Figure 12. Comparison of Figure 12 with Figure 9 reveals that the devices in these figures are essentially the same except that the grating substrate 12 in

device 160 of Figure 9 is replaced in device 210 of Figure 12 by the beam expanding prism element 212 and that the grating 15 is now deposited on the input optical transmitting surface of the glass block 152 in device 210. With regard to the dual pass grating diffraction properties, the device 210 functions as described for the devices illustrated in Figures 7, 8 and 9. As depicted in Figure 12, a single collimated wavelength beam 162 is incident on the device 210 at the Littrow diffraction condition for the device 210 arrangement and is retrodiffracted back along the incident beam 162 as beam 166. Referring to Figure 12, it will be seen that the prism element 212 expands the size of the incident beam 162 prior to that beam being incident on the grating surface 15 and since prism 212 functions in a reversible manner it reduces the size of the beam 214 rediffracted from grating 15.
The increase in the wavelength dispersion power of device 210, relative to that achieved with the devices of Figures 7, 8 and 9, is determined by how much the prism element 212 reduces the size of the beam 166 exiting from the prism 212 relative to the size of the beam 214 propagating within prism 212.

With the device 210 of Figure 12, one can achieve a wavelength dispersion power that is equal to an effective λ/D ratio value in the range of about 2.0 to 4.8 and still achieve essentially equal diffraction efficiency values for S and P polarized optical components. One can achieve high radiometric throughput efficiency for the prism element 212 for both S and P optical polarization by applying antireflection coatings to the optical transmitting surfaces of the prism. As depicted in Figure 12, the non-optical transmitting and reflecting surfaces of glass block 152 and prism element 212 have been coated with an optical absorption coating 156 that is designed to absorb the nondiffracted zeroth order beam energy and other scattered and reflected light which may occur within elements 152 and 212.

Associated with the beam size reducing property of prism element 122 of device 210. is the additional benefit with regard to linearizing the spacing of the spatially separated focused wavelength channel signal beams at either the photodetector array element in a wavelength monitoring device or at the output fiber-optic array in a Demux device. The wavelength channels of a WDM fiber-optic system are separated by a fixed frequency spacing, such as 200, 100 or 50 GigaHertz, but have a wavelength spacing between adjacent wavelength channels that varies slightly as a function of the frequency (wavelength) of the wavelength channel. For example, the wavelength spacing between adjacent wavelength

channels of a WDM fiber-optic system having a 100 GigaHertz frequency spacing between channels is approximately 0.86, 0.80 and 0.78 nanometers, respectively, for wavelength channels having wavelengths in the range of 1611, 1552, and 1530 nanometers.

This slight variation in wavelength spacing between the adjacent wavelength channels in a WDM fiber-optic system produces a corresponding non-equal spacing variation in the spatial separation between the focused wavelength channel beams incident on the photodetector arrays in the wavelength monitoring devices depicted in Figures 5, 6, 11A, 11B and 11C and in the spatial separation between the focused wavelength channel beams incident on the fiber-optic output array in the Demux device depicted in Figures 10A, 10B and 10C. The prism element 122 of device 210 can be designed so that it linearizes the diffracted angular spacing between the wavelength channel beams exiting from the prism element 122 and, thereby, enables Demux and wavelength monitoring devices that incorporate device 210 to utilize a linear spacing between adjacent channels in their output arrays.

Given its relatively high radiometric throughput efficiency, its high effective λ/D value, and its linearizing properties, the device 210 of Figure 12 provides significant advantages for use in WDM fiber-optic communication systems having 100, 50 or 25 GigaHertz spacing between wavelength channels. Beam expanding prism elements are used to increase the wavelength dispersion resolution of grating-based wavelength tunable dye laser systems, as shown in an article by F. J. Duarte, "Newton, Prisms, and the "Opticks" of Tunable Lasers," Optics and Photonics News, May 2000.

Schematically illustrated in Figure 13 is spectrophotometer device 217A that is essentially identical to the spectrophotometer device 120 of Figure 6 with the expectation that the device 217A incorporates a linearizing prism element 218 that functions similar to the prism element 122 of device 210 in Figure 12. The prism element 218 differs somewhat from the prism element 122 in that the angles of the prism have been changed so that the diffracted beam from grating element 10 is substantially perpendicular to the input surface of prism element 218. Due to this prism angle change, the prism element 218 is not attached to the grating element 10, as was the case for the prism element 212 of device 210. As depicted in Figure 13, prism element 218 has the same beam size reducing property as described for prism element 212 of device 210 which increases the wavelength dispersion power of device

217A and provides the benefit with regard to linearizing the spacing of the spatially separated focused wavelength channel signal beams at the photodetector array 94 of device 217A. As also depicted in Figure 13, the non-optical transmitting surfaces of prism element 218 have been coated with an optical absorption coating that is designed to absorb any non-diffracted zeroth order beam energy that might enter the prism and other scattered and reflected light which may occur within prism element 218.

As depicted in Figure 13, the prism element 218 reduces the size of the beam exiting prism element 218 by about 1.65 times compared to the beam propagating within the prism element. The angular separation between the wavelength channel beams exiting prism element 218 is approximately 1.65 $d\theta_d$ where $d\theta_d$ is the diffracted angular separation between wavelength beams exiting the grating element 10 as calculated by Equation (2). Prism element 218 increases the wavelength dispersion power of device 217A by approximately 1.65 times that achieved by device 120 of Figure 6. Therefore, device 217A can achieve the same spatial separation between focused wavelength channel beams at the photodetector array 94 that device 120 achieves, but can achieve this separation using a focusing lens assembly 92 that has a focal length that is approximately 1.65 times shorter than the corresponding focal length used in device 120.

Prism element 218 provides additional benefit with regard to linearizing the spacing of the spatially separated focused wavelength channel beams at the photodetector array 94. Analysis has shown that when the spectrophotometer device 120 of Figure 6 is used to monitor the signal of a WDM fiber-optic system having a 100 GigaHertz frequency spacing between wavelength channels, the spatial separations between the focused wavelength channel beams at the photodetector array 94 in device 120 are non-equally spaced and, therefore, do not match the 25 or 50 micron equally spaced intervals between the photosensitive elements of commercial available InGaAs photodetector linear arrays.

To illustrate the non-equal spacing error in the spatially separated focused wavelength channel beams in device 120, it is assumed that the spatial separated focused channel beams in device 120 are incident on adjacent photosensitive elements in the photodetector array 94 and that these elements have a 50 micron spacing between element centers, that the device 120 incorporates a surface-relief transmission grating element 10 having a λ/D ratio of 1.0 for an optical wavelength of 1550 nanometers, that $\theta_i = \theta_d = 30$ degrees for a wavelength of 1550

nanometers and that the focusing lens assembly 92 in this device has a focal length of approximately 84 millimeters. When this device 120 configuration is used to monitor a WDM fiber-optic system beam having 100 different wavelength channel signals each spaced by 100 GigaHertz and having a wavelength spectrum from about 1530 to 1612 nanometers, calculations indicate that the non-equal spacing error between the adjacent focused wavelength channel beams at the photodetector array 94 accumulates and results in a total spacing error of approximately 49 microns between the shortest and longest focused wavelength channel signal beams. That is, if the photodetector array 94 in device 120 is positioned so that the shortest wavelength channel signal beam is incident on the center of the first photosensitive element of the photodetector array 94, the longest wavelength channel signal beam will land approximately 49 microns from the center of the hundredth photosensitive element of the photodetector array 94, with progressively shorter wavelength channel signal beams having progressively smaller positional errors with respect to the photosensitive element on which they are supposed to be incident on in the photodetector array 94. This 49-micron positional error is not acceptable.

Calculations show that when spectrophotometer device 217A of Figure 13 is used to monitor a WDM fiber-optic system beam having 100 different wavelength channel signals each spaced by 100 GigaHertz and having a wavelength spectrum from about 1530 to 1612 nanometers, the spatially separated focused wavelength channel signal beams at the photodetector array 94 have substantially the same 50 micron spacing between all the wavelength channel signal beams, with about a total 1 micron spacing error between the shortest and longest wavelength channel signal beams, when the following configuration conditions are assumed for device 217A. Device 217A incorporates a surface-relief transmission grating having a λ/D ratio of 1.0 with $\theta_i = \theta_d = 30$ degrees for an optical wavelength of 1550 nanometers, the prism element 218 has an index of refraction of approximately 1.51 with θ_1 being approximately 35 degrees and θ_2 being approximately 60 degrees which corresponds to a beam size reduction by prism element 218 of approximately 1.65 times, and that the focusing lens assembly 92 has a focal length of approximately 50 millimeters. The maximum total error spacing of approximately 1 micron between the shortest and longest wavelength channel signal beams at the photodetector array 94 for this device configuration is very acceptable since each photosensitive element in a photodetector

array having a 50 micron spacing between photosensitive elements has a photosensitive area width along the array equal to the element spacing of 50 microns and, therefore, a positional error in the range of 1 to 2 microns still places the focused wavelength channel beam essentially in the middle of the photosensitive element.

Schematically illustrated in Figure 14 is spectrophotometer device 217B that is essentially identical to the spectróphotometer device 217A of Figure 13 with the expectation that the linearizing prism element 219 of device 217B now incorporates the transmission surface-relief grating 15. The prism element 219 performs the same functions as the combination of the grating element 10 and prism element 218 of device 217A and, therefore, device 217B functions as described for device 217A.

While there are advantages associated with combining the functions of the grating element 10 and prism element 218 of device 217A into the single prism element 219 of device 217B, the prism element 219 does not provide as good results as the separate grating and prism elements provide with regard to passively athermalizing the performance of the spectrophotometer device so that it meets operating specifications when used over the 70 degree centigrade temperature range specified for fiber-optic telecommunication applications without the need for active control. The reason why the separate grating element 10 and the separate prism element 218 provide better results than the dual functioning prism element 219 with regard to athermalizing device performance is that the grating element achieves the best athermalization performance when fabricated using a substrate material having a low thermal expansion coefficient, such as fused silica or ULE glass, while the linearizing prism element achieves the best athermalization performance when fabricated using a glass material having a low thermal coefficient of refraction (dn/dT), such as BK7 and K5 glasses. Unfortunately, low thermal expansion glasses such as fused silica, ULE and Ohara Clearceram-Z have a thermal coefficient of refraction that is approximately 10 times larger than that achieved with K5 glass and about 5 times larger than that achieved with BK7 glass. Optical glasses such as BK7 and K5 have a thermal coefficient of thermal expansion that is approximately 10 times larger than that achieved with fused silica and about 50 to 100 times greater than that achieved with ULE or Ohara Clearceram-Z. Therefore, as the preceding discussion illustrates, better athermalization of device performance is achieved by using different glass materials for the grating and prism elements which dictates that they be

fabricated as separate components to avoid thermal-induced stress associated with the optical bonding of materials having significantly different thermal expansion coefficients.

The doubling of the angular wavelength dispersion power of the transmission grating elements in Figures 7, 8, 9 and 12 was accomplished by reflecting the diffracted beam back through the grating element. One can achieve this doubling of grating dispersion power by cascading two separate transmission grating elements, that is, physically arranging two surface-relief transmission grating elements so that a beam diffracted by the first grating element undergoes diffraction by the second grating element. One could further increase the wavelength dispersion power of transmission grating-based devices by cascading multiple grating elements. For example, one could achieve effectively four times the wavelength dispersion power of a grating element by physically cascading four individual transmission grating elements or by reflecting the diffracted beam back through two cascaded transmission grating elements. The only significant negative associated with this multiple cascaded transmission grating technique is the radiometric efficiency loss associated with the multiple diffraction events. Surface-relief grating-based devices utilizing physically cascaded grating elements are illustrated in Figures 15 through 24.

One of the potential advantages of the physically cascaded grating arrangements in Figures 15 through 24 relative to the dual pass grating arrangements in Figures 7 through 12, is that different λ/D ratio values can be used for the individual grating elements used in the physically cascaded grating arrangements in Figures 15 through 23. It should also be noted that the physically cascaded gratings in Figures 15 through 23 are arranged so that the wavelength dispersion power of the device incorporating the gratings is essentially equal to the sum of the wavelength dispersion power of the individual gratings used in the device. The gratings in these devices are arranged so that the beam diffracted from the first grating is incident on the second grating so that its angle of incidence is on the same relative side of the normal to the second grating surface that the incident beam makes relative to the normal of the first grating surface. That is, as illustrated in Figures 15 through 23, the beam is always incident on the right side of the normal to the grating surfaces as viewed in the beam propagating direction. The cascaded grating arrangements in Figures 15 through 23 are arranged so that the individual grating elements in these arrangements are operated relatively close to the Littrow direction condition.

Figure 15 is a schematic of a dual pass cascaded grating-based wavelength selection device 220 which is similar to the device 130 depicted in Figure 7 but differs therefrom in replacing the mirror element 122 in device 130 with a surface-relief reflection diffraction grating element 222 in device 220. This modification significantly increases the wavelength dispersion power of the device 220 relative to that of device 130 of Figure 7. The incident beam 84 to the transmission grating element 10 in device 220 contains λ_1 and λ_2 wavelength components. After the incident beam 84 is diffracted by the grating element 10, these optical wavelength components are angularly separated by $\Delta\theta$. The grating element 222 is angularly orientated so that the λ_1 wavelength beam 132 is retrodiffracted back on itself, that is, the grating element 222 operates at the Littrow condition, $\theta_i = \theta_d$, for the λ_1 wavelength beam 132. Because the grating element 10 functions in a reversible manner, the grating element 10 rediffracts the retrodiffracted λ_1 wavelength beam 132 back along the direction of the incident beam 84 as beam 134. This dual pass transmission multi-grating arrangement mimics a single reflection grating element operating at the Littrow condition for the λ_1 wavelength beam, since this beam is retrodiffracted back on itself. After diffracting from the grating element 222, the λ_2 wavelength beam 136 propagates back to the grating element 10 where, due to its angle of incidence, the λ_2 wavelength beam 136 is rediffracted from the grating element 10 with an angle equal to approximately $3\Delta\theta$ relative to the propagating direction of the retrodiffracted λ_1 wavelength beam 134 when the transmission grating element 10 and the reflection grating element 222 have approximately the same λ/D ratio values.

Essentially equal diffraction efficiency values for S and P polarized optical components can be achieved for sinusoidal surface-relief reflection gratings when their λ/D ratio is in the range of about 0.7 to 0.85. This reference also shows that surface-relief reflection gratings having a triangular blazed grating line groove profile achieve essentially equal diffraction efficiency values for S and P polarized optical components when these gratings have λ/D ratio values of between about 0.1 to 0.85. Approximately 0.85 is the largest λ/D ratio value that can be used with surface-relief reflection gratings and still achieve essentially equal diffraction efficiency values for S and P polarized optical components. Therefore, one may elect to use a surface-relief reflection grating element 222 in device 220

having a λ/D value of about 0.8 in combination with a surface-relief transmission grating element 10 that has a λ/D value of between 0.8 and 1.2 and, thereby increase the effective λ/D ratio value of device 220 while still achieving essentially equal diffraction efficiency values for S and P optical polarizations.

Using the dual pass multi-grating combination in device 220, a surface-relief grating-based device can be constructed with effective λ/D grating values of 2.3 to 3.2 while achieving essentially equal diffraction efficiency values for S and P polarized optical components. The dual pass multi-grating combination device 220 achieves these effective high λ/D values by cascading the grating dispersion power of the grating elements in the device, that is, the effective λ/D value is the sum of the λ/D values of the individual grating elements that the beam is diffracted by. In Figure 15 the beam undergoes three diffractions since the beam is passed twice through grating element 10. This cascading of the grating dispersion power does not effect the wavelength filter function of the grating-based devices incorporating this cascaded grating arrangement, since the wavelength filter function of these devices is determined by the physical dimensions of the output array structures used in those devices.

Referring again to Figure 15, one can change the wavelength of the beam 134 retrodiffracted back on itself and, thus change the wavelength tuning parameters of the device 220, by rotating the grating element 222 in the direction of arrow 138 and/or arrow 140 by conventional means, as was also described in regards to Figure 7.

As illustrated in Figure 16, one can configure the device 220 of Figure 15 using a solid glass block element 232 that incorporates a surface-relief transmission grating 15 and a surface-relief reflection grating element 222 that is attached to the output optical transmitting surface of glass block 232. The dual pass multi-grating device 230 of Figure 16 functions as described for the device 220 of Figure 15. As depicted in Figure 16, a single collimated wavelength beam 162 is incident on the dual pass multi-grating device 230 at the Littrow diffraction condition for the device 230 arrangement and is retrodiffracted back along the incident beam 162 as beam 166. A sealing element 168, such as epoxy, is used in device 230 to encapsulate the air gap layer 170 that exists between the surface-relief reflection grating surface of element 222 and the output optical transmitting surface of the glass block element 232. The main function of the sealing element 168 is to prevent contaminants, liquids or

solvent vapors that could damage the grating surface from entering the air gap layer 170; and not every sealing element will function well in this device. The output optical transmitting surface of the glass block 152 has to be antireflection coated to minimize optical reflection losses at that surface. As depicted in Figure 16, the non-optical transmitting surfaces of the glass block 152 have been coated with an optical absorption coating 156 that is designed to absorb the nondiffracted zeroth order beam energy and other scattered light which may occur within the glass block element 152.

Figure 17 is a schematic view of a dual pass multi-grating device 240 similar to the device 230 depicted in Figure 16 but differing therefrom in that the transmission grating surface 15 in device 240 is encapsulated between the substrate 12 of grating element 10 and the input optical transmitting surface of glass block element 232 to which element 10 is attached, similar to manner shown in the device 160 of Figure 9. Furthermore, the surface-relief reflection grating element 222 is directly attached (by, e.g., adhesive means, such as optical cement) to the glass block 232. The device 240 functions exactly as described for the device 230 of Figure 16, except that the surface-relief reflecting grating surface of element 222 of device 240 is immersed in the optical cement used to optically bond element 222 to element 232. Under these immersed grating conditions, the effective λ/D of the grating element 222 is reduced by the index of refraction of the optical cement used to bond the grating element 222 to the glass block 232. One can compensate for the reduction in the λ/D of the grating element 222 as a result of being immersed in a media having an index of refraction larger than the 1.0 value for air by starting with a grating element 222 that has a higher λ/D value. Typically one starts with a λ/D value that is n times larger than the effective the λ/D value that one wants to achieve for the immersed grating element, where n is the refractive index of the cement used to bond element 222 to element 232. Most optical cements have a refractive index in the range of about 1.45 to 1.6. For example, if one wants to have an immersed sinusoidal surface-relief reflection grating element 222 that has an effective λ/D value of about 0.8 and, thereby, achieve essentially equal diffraction efficiency values for S and P polarized optical components, one would start with a grating element having a λ/D value of about 1.2, assuming that the optical cement used to bond element 22 to element 232 in device 240 had an index of refection of 1.50.

Figure 18 illustrates how one can achieve the doubling of grating dispersion power by physically cascading two surface-relief transmission gratings 15 and 15', i.e., physically arranging two transmission grating elements so that a beam diffracted by the first grating undergoes diffraction by the second grating. The two gratings 15 and 15' are deposited onto the input and output optical transmitting surfaces of the glass block element 252. The single wavelength collimated incident beam 162 is diffracted by the first grating 15 as beam 254. The collimated diffracted beam 254 propagates in the glass block element 252 and is incident upon the second diffraction grating 15', which diffracts the beam 254 as collimated beam 256. The non-optical transmitting surfaces of the glass block 252 are coated with an optical absorption coating 156 that is designed to absorb the nondiffracted zeroth order beam energy and other scattered light that may occur within the glass block element 252.

The wavelength dispersion power of the dual cascaded transmission grating element 250 is essentially the sum of the wavelength dispersion powers of each of the gratings 15 and 15'. That is, the device 250 has an effective λ/D value which is equal to the sum of the λ/D values for the individual grating elements 15 and 15' used in the device. One can achieve essentially equal diffraction efficiency values for S and P polarized optical components for the element 250 by using surface-relief transmission gratings 15 and 15' that each have a λ/D ratio in the range of about 0.8 to 1.2, as shown by the data in Figure 4. Using this λ/D value range for gratings 15 and 15', the element 250 can have an effective λ/D ratio value of about 1.6 to 2.4 and achieve essentially equal diffraction efficiency values for the S and P optical polarization components.

The spectrophotometer device 260 of Figure 19 is essentially identical to the spectrophotometer device 217A of Figure 13 with the exception that diffraction grating element 10 of device 217A is replaced in device 260 with the dual cascaded transmission grating element 250 of Figure 18. Also, the linearizing prism element 218 and the beam fold mirror element 122 of device 217A have been combined into the single prism element 262 in device 260 that performs the dual functions of beam fold mirror and linearizing prism element. The dual functioning prism element 262 can achieve good athermalization performance since fabricating it with a glass material having a low thermal coefficient of refraction does not affect the beam folding mirror function of the element. Because the grating element 10 in Figure 13 is replaced with element 250 in device 260, device 260

effectively has approximately twice the wavelength dispersion power as that achieved with device 217A. The higher wavelength dispersion power of the device 260 enables this device to utilize a shorter focal length for the focusing lens assembly 92 in the device and/or the device can be used in WDM fiber-optic communication systems having finer wavelength spacing between wavelength channel signals. The ability to work with WDM systems having finer spacing between their wavelength channel signals is becoming more important since the space between wavelength channels in fiber-optic communication systems is continuing to decrease.

Figure 20 illustrates a dual cascaded transmission grating device 270 which is similar to the device 250 of Figure 18 but differs from that device by using surface-relief transmission grating elements 10 and 10' that are, respectively, attached to the input and output optical transmitting surfaces of glass block 252. The grating surfaces of elements 10 and 10' are encapsulated using sealing element 168 in substantial accordance with the method used to encapsulate the grating surface of element 10 in device 160 of Figure 9. The device 270 functions as described for the device 250 of Figure 18.

Figure 21 illustrates a dual pass multi-grating device 280 that is similar to the device 130 of Figure 7 but replaces the diffraction grating element 10 of device 130 with dual cascaded grating device 270 of Figure 20. As depicted in Figure 21, a single collimated wavelength beam 162 is incident on the device 280 at the Littrow diffraction condition for the device 280 arrangement and is retrodiffracted back along the incident beam 162 as beam 166. Device 280 functions essentially as described for device 130 of Figure 7 with the exception that the wavelength dispersion power of the device 280 is substantially two times as great as that achieved with device 130 for the case where the grating elements 10 and 10' of device 280 have the same λ/D value as the grating element 10 in device 130. The device 280 can have an effective λ/D ratio of about 3.2 to 4.8 and still achieve essentially equal diffraction efficiency values for S and P polarized optical components by using grating elements 10 and 10' that each have λ/D values in the range of about 0.8 to 1.2.

Figure 22 illustrates a dual pass multi-grating device 290 that is similar to the device 220 of Figure 15 but replaces the diffraction grating element 10 of device 220 with dual cascaded grating device 270 of Figure 20. As depicted in Figure 20, a single collimated wavelength beam 162 is incident on the device 290 at the Littrow diffraction condition for the

device 290 arrangement and is retrodiffracted back along the incident beam 162 and beam 166. Device 290 functions essentially as described for device 220 of Figure 15 with the exception that the dispersion wavelength power of the device 220 is approximately 1.67 times greater than that achieved for the device 220 for the case where device 220 and device 290 use grating elements having essentially the same λ/D values. The device 290 can have an effective λ/D ratio of about 5.0 to 8.8 and still achieve essentially equal diffraction efficiency values for S and P polarized optical components when the surface-relief transmission grating elements used in the device each have λ/D values of about 0.8 to 1.2 and the surface-relief reflection grating element 222 has a λ/D value of about 0.7 to 0.85.

The transmission multi-grating device 300 depicted in Figure 23 is similar to the device 270 in Figure 20, with the exception that the dispersion power has been further increased by stacking a third diffraction grating element 10'' to the grating elements 10 and 10' that are incorporated in device 270 of Figure 20. Device 300 functions as described for the device 270 of Figure 20 with the exception that, in device 300, the collimated beam 256 diffracted from grating element 10' propagates in the glass block 252' to grating element 10'' where it is diffracted as collimated beam 302. The effective λ/D ratio value for the device 300 is essentially equal to the sum of the λ/D values for the individual grating elements 10, 10' and 10''. Therefore, device 300 can be fabricated with an effective λ/D ratio value of about 2.4 to 3.6 while still achieve essentially equal diffraction efficiency values for S and P polarized optical components by using surface-relief transmission grating elements for gratings 10, 10' and 10'' that each have λ/D values in the range of about 0.8 to 1.2.

In device 300 the individual grating elements 10, 10' and 10'' are attached to the corresponding optical transmitting surfaces of glass block elements 252 and 252' using sealing elements 168. Sealing elements 168 encapsulate the grating surfaces of elements 10, 10' and 10'' in substantial accordance with the method used to encapsulate the grating surface of element 10 in device 160 of Figure 9. As depicted in Figure 23, grating element 10' is optically attached to glass block 252'. One could use optical cement to bond grating element 10' to glass block 252' or one could directly optically contact grating element 10' to glass block 252'.

As depicted in Figure 23, the substrate material of grating element 10' and the glass block 252' have essentially the same index of refraction and, therefore, the beam 256

propagates from grating element 10' into glass block 252' as if the combination of elements 10' and 252' were fabricated from a single continuous glass block element for the case where these elements are either optically contacted together or bonded using an optical cement that has an index of refraction that is essentially equal to that of the refractive indices used for elements 10' and 252'. For the case where the grating element 10' and glass block element 252' have different indices of refraction and/or the optical cement used to bond elements 10' and 252' together has a different index of refraction relative to the indices of refraction for elements 10' and 252', the beam 256 propagates from grating element 10' into glass block element 252' but some of its intensity is lost due to the reflection loss that occurs at the interface boundary surface between materials that have different indices of refraction. These reflection losses are less than 0.5 percent per interface boundary surface when the indices of refraction for elements 10' and 252' and the optical cement used to bond them together are relatively close, that is, when the difference in these indices of refraction are less than approximately 0.2 for materials having an index of refraction in the range of about 1.40 to 1.70.

The optical bonding of grating element 10' to glass block element 252' in device 300 of Figure 23, in effect, creates a surface-relief transmission grating surface on the input optical transmitting surface of block element 252'. While this technique for creating a grating surface on the optical transmitting surface of a glass block element is only illustrated in Figure 23, it can be used to create the transmission grating surface 15 on the input optical transmitting surface of the glass blocks in Figures 8, 12, 14 and 16 and the grating surfaces 15 and 15' on the input and output optical transmitting surfaces of glass block 252 in Figure 18. This method of creating a surface grating 15 on the input and/or output transmitting surfaces of a glass block by optically bonding a grating element 10 to the surface of the glass block element provides significant advantages with regard to manufacturing the grating surfaces 15 on the input optical transmitting surfaces of the glass blocks in Figures 8, 12, 14 and 16 and the grating surfaces 15 and 15' on the input and output optical transmitting surfaces of the glass block in Figure 18.

It is much easier to create a surface-relief photoresist grating on a parallel plate substrate element than to create a surface-relief photoresist grating on a non-parallel shaped glass block element. Also, multiple surface-relief photoresist grating elements can be

fabricated on a single large substrate element, in the same manner that multiple integrated circuit elements are fabricated on a single silicon wafer. A large substrate containing multiple grating elements can be cut up to yield smaller grating elements having a size suitable for the devices that they will be used with. These grating elements cut from the larger substrate element can be used as a stand alone element as illustrated in Figures 5, 6, 7 and 15, attached to a glass block element with an air spacing layer between the grating surface and the optical transmitting surface of the glass block element as illustrated in Figures 9, 16, 17, 20, 21 and 23, or optically bonded to a glass element as illustrated in Figure 23, and, while not specifically illustrated, used to create the grating surface on the glass block elements incorporated in the devices illustrated in Figures 8, 10A, 10B, 11A, 11B, 12, 14, 16, and 17.

One can further increase the wavelength dispersion power of the transmission multi-grating device 300 of Figure 23 by either adding another transmission grating element to the device, incorporating a beam fold mirror in the device that retroreflects the diffracted beam 302 back through the device or by incorporating a reflecting grating element in the device that retrodiffracts the diffracted beam 302 back through the device. It is anticipated that the wavelength dispersion power of the devices shown in this specification are suitable for both present and future grating-based devices used in fiber-optic communication systems.

Figure 24 illustrates a dual cascaded transmission grating device 310 which is similar to the device 250 of Figure 18. Device 310 functions essentially as described for device 250 with the exception that the beam 254 diffracted from grating 15 undergoes two reflections within the glass block element in device 310 before being incident on grating 15' which diffracts it as beam 256. As depicted in Figure 24, the glass block element of device 310 is composed of two glass block elements 312 and 314 that are optically bonded together. Glass block elements 312 and 314 are fabricated from the same type of glass material and are bonded together by being either directly optically contacted or by using an optical cement that has an index of refraction that is essentially equal to the refractive index of glass block elements 312 and 314 and, thereby forms essentially a single continuous glass block element. The block element 312 is a roof prism element having a 90-degree angle between its reflective mirror coated surfaces 154 and 154'. The block element 314 is a prism element having a base length that matches the length of the hypotenuse leg of block element 312

while the enclosed angle between the other two leg surfaces of element 314 is chosen to facilitate the diffraction angle conditions of device 310.

Device 310 is included in this specification to illustrate that beam folding mirror surfaces can be incorporated into the cascaded multi-grating devices presented in this specification and, thereby, change the angular propagation path that the beam undergoes with the device and the angular direction of the beam exiting the device relative to the incident beam direction. Comparison of device 310 in Figure 24 with device 250 of Figure 18 shows that the inclusion of beam folding mirror surfaces as implemented in the embodiment in Figure 24 does not essentially affect the wavelength dispersion power of the device.

One of the most fundamental operations in a communication network is the selective switching (add/drop) of signals between different transmission paths of the network. A number of techniques have been demonstrated for building optically based add/drop wavelength multiplex (ADWM) devices that optically switch different wavelength channels between different fiber ports in a WDM fiber-optic communication system. United States Patent 5,960,133 discloses methods for building ADWM devices that utilize reflection grating elements to perform the wavelength channel selection function in these devices.

Schematically illustrated in Figures 25A and 25B is an ADWM device 320 that is similar to the device 19 in Fig. 2 of United States Patent 5,960,133, but differs from that device in that device 320 uses dual cascaded transmission grating element 270 of Figure 20 in place of the reflection grating element used in the Fig. 2 device 19 of United States Patent 5,960,133. Because the elements used to fabricate the input and output ports and the micro electromechanical (MEM) mirror switching elements of the ADWM devices disclosed in United States Patent 5,960,133 are relatively large, these ADWM devices can benefit from the flexibility of element placement provided by replacing the reflection grating elements used in the ADWM devices of United States Patent 5,960,133 with surface-relief transmission grating-based elements, in the same manner that the wavelength channel monitoring devices of Figures 5 and 6 benefit from the use of transmission grating element 10. These ADWM devices can also benefit from the increased wavelength dispersion power provided by the cascaded transmission grating arrangements presented in this specification, as illustrated by device 320 in Figures 25A and 25B.

With reference to Figure 25A, ports P1 and P2 provide generally parallel but separate optical beams 322 and 324 that are incident to the dual cascaded grating element 270. Beams 322 and 324 contain λ_1 and λ_2 wavelength channel signals. After diffraction from element 270 the incident beams 322 and 324 are separated into their respective wavelength components. The λ_1 wavelength components of beams 322 and 324 are, respectively, 326 and 326' and are depicted in Figure 25A as solid lines while the λ_2 wavelength components of beams 322 and 324 are, respectively, 328 and 328' and are depicted as dashed lines in Figure 25A. As illustrated in Figure 25A, the diffracted beams having different wavelengths are angularly separated while those of the same wavelength remain substantially parallel. A lens 334 focuses all of the beams from element 270 onto a micro-mirror array 336 comprising separately tiltable micro-mirror elements 338 and 340.

In the first position of the micro-mirror elements 338 and 340, illustrated in Figure 25A by the solid lines, the mirror elements 338 and 340 reflect both wavelength beams received from port P1 directly back to port P1 as beam 330. That is, in this first position the mirrors are orientated perpendicular to the beams 326 and 328. For this first mirror position no wavelength signal channels are either added to or dropped from port P1 of the device 320. However, when mirror elements 338 and 340 are in the second position, illustrated by the dotted lines in Figure 25A, the mirror elements 338 and 340 reflect wavelength beams received from port P1 to port P2. That is, in the second position the mirror element 338 is orientated perpendicular to the bisector of the beams 326 and 326' and the mirror element 340 is orientated perpendicular to the bisector of the beams 328 and 328'. In the second position, the mirror elements 338 and 340 also reflect wavelength beams received from port P2 to port P1. For this second mirror position both the λ_1 and λ_2 wavelength channel signals of beam 322 are dropped from port 1 and added to port 2 while both the λ_1 and λ_2 wavelength channel signals of beam 324 are dropped from port 2 and added to port 1.

Figure 25B illustrates the case where mirror element 338 of device 320 is orientated in the first position, same as illustrated in Figure 25B, while mirror element 340 is orientated in the second position. For the mirror orientation arrangement in Figure 25B, the λ_1 wavelength beam from port 1 is reflected back to port 1 and comprises part of beam 330' while the λ_2 wavelength beam from port 1 is reflected to port 2 as beam 332 and the λ_2 wavelength beam from port 2 is reflected to port 1 and comprises part of beam 330'. For the

mirror arrangement in Figure 25B, the λ_2 wavelength channel signal of beam 322 is dropped from port 1 of device 320 and added to port 2 of the device while the λ_2 wavelength channel signal of beam 324 from port 2 is added to port 1 of the device. While only two wavelength channel signals and only two micro-mirror elements are depicted in device 320 of Figures 25A and 25B, it is evident that device 320 can be fabricated with a micro-mirror array 336 having a large number of micro-mirror elements and, thereby enable device 320 to be used to add/drop a large number of wavelength channel signals.

As stated in United States Patent 5,690,133, the device 19 of Fig. 2 of that patent, that is similar to that of device 320 of Figures 25A and 25B, has many desirable characteristics but suffers from some problems. One problem being that optical circulator devices have to be connected to the ports P1 and P2 to separate wavelength beam signals going in opposite directions. Optical circulator devices are expensive and add optical insertion loss to the ADWM device. A further problem with the device 320 is that it cannot simultaneously direct the λ_1 wavelength beam from port P1 to port P1 while directing the λ_1 wavelength beam from port P2 to port P2, or perform this same simultaneous switching function for the same wavelength for any of the other wavelength channel beams in the device.

Fig. 5 in United States Patent 5,960,133 shows what is claimed as an improved micro-mirror based add/drop device relative to the device 19 of Fig.2 of this patent. Schematically illustrated in Figure 26 is an ADWM device 350 that is similar to the Fig. 5 device in United States Patent 5,960,133, but differs from that device in that device 350 uses dual cascaded transmission grating element 270 in place of the reflection grating element used in the Fig. 5 device of United States Patent 5,960,133. The device 350 functions similar to that stated for device 320 of Figures 25A and 25B, with the exception that device 350 uses four parallel, direction, input and output beam paths 352, 354, 356, and 358 arranged in a two-dimensional array. The four beams in this arrangement are the input beam 352, the output beam 354, the add beam 356, and the drop beam 358. The input and add beams 352 and 356 propagate oppositely from the output and drop beams 354 and 358.

As explained in United States patent 5,960,133, the incorporation of the four parallel beam paths 352, 354, 356, and 358 into device 270 enables this add/drop device to function without the need for optical circulator devices and enables the device 350 to simultaneously switch a λ_1 wavelength channel signal from the input beam path 352 to the drop beam path

358 while switching a λ_1 wavelength channel signal from the add beam path 356 to the output beam path 354.

Replacement of the reflection grating elements in the Fig. 2 and Fig. 5 devices of United States Patent 5,960,133 with a surface-relief transmission grating or a dual cascaded transmission grating element, as illustrated in Figures 25A, 25B and 26, does not change the basic add/drop functions of these devices but improves device layout configuration while providing increased wavelength dispersion power, which becomes increasingly important as the wavelength spacing in WDM fiber-optic systems decreases.

A schematic side view is illustrated in Figure 27A of a Mux/Demux device 360 that is similar to the device shown in Figure 1 of a paper by S. Bourzeix, et al. entitled "Athermalized DWDM Multiplexer/Demultiplexer," (2000 National Fiber Optic Engineers Conference Technical Proceedings, Vol. 2, pages 317-320), but differs primarily from that device in that device 360 uses surface-relief transmission grating element 10 in place of the surface-relief reflection grating element used in the Figure 1 device of the Bourzeix, et al. paper. The use of transmission grating element 10 in device 360 facilitates the placement of the dihedral retroreflecting mirror element 374 in relation to the grating element 10 while enabling the grating to operate closer to the Littrow diffraction condition, relative to that achieved when a reflection grating element is incorporated into the device. Also, the use of transmission grating element 10 of Figure 27A enables the dihedral mirror element 374 of this figure to be incorporated into a glass block element that includes the transmission grating, similar to the arrangement illustrated in Figures 8 and 9. It is much more difficult to incorporate the dihedral mirror element into a glass block element that includes the grating when a reflection grating is used in the device.

As depicted in Figure 27A, input optical wavelength channel signal information is delivered to device 360 by transmission fiber 182. Input fiber 182 and output fibers 362 are held and spatially positioned relative to each other and the other optical components in device 360 by the fiber-optic array element 364. The optical beam emerging from the end of input fiber 182 is incident on a lens element (not shown) in the microlens array 366. Microlens array 366 reduces the divergence angle of the beam from input fiber 182 by about 1 degree, which increases the relative channel width of the device. Beam 367 from the microlens array 366 is collimated by lens 368. The collimated beam 367 from lens 368 propagates through

the birefringent crystal element 370, through the halfwave retardation plate 372, to the grating element 10 where the beam is diffracted to the dihedral mirror element 374, the retroreflected beam from mirror element 374 propagates back to grating element 10 where it is rediffracted and propagates back through the halfwave retardation plate 372 and birefringent crystal element 370 to lens 368. The converging beam 376 from lens 368 is incident on microlens array 366, which focuses the angularly separated wavelength channel beams of beam 376 onto their corresponding output fibers 362 held in the fiber-optic array element 364.

A schematic top view in Figure 27B of a portion of the device 360 more clearly illustrates how the birefringent crystal element 370, halfwave retardation plate 372 and dihedral mirror element 374 collectively function together to control the polarization direction of the optical beam incident on grating element 10 and, thereby, enable the device 360 to achieve radiometric throughput efficiency values for S and P polarizations that are equal to within about 5 percent of each other. As depicted in Figure 27A, the incident beam to grating element 10 and the diffracted beam from grating element 10 both make an angle of about 45 degrees with regard to the normal to the surfaces of element 10. Therefore, the grating element 10 in device 360 has a λ/D ratio value of approximately 1.4142, which according to the data in Figure 4 results in the S polarized optical beam having almost 100 percent diffraction efficiency while the P polarized beam has almost zero percent diffraction efficiency. For the configuration depicted in device 360, essentially only the S polarized optical component is diffracted from grating element 10 and, therefore, the other optical elements collectively function together to ensure that only a S polarized beam is incident on the grating element 10.

With reference to Figure 27B, the incident beam 367 to the birefringent crystal element 370 is composed of both S and P polarized optical components where the P component 378 is depicted as an ellipse with a dot at its center while the S component 380 is depicted as a bold arrow figure. Only the S and P polarization components to the left of element 370 in Figure 27B are labeled with their respective numbers 380 and 378. When beam 367 propagates through the birefringent crystal element 370 its S and P polarized optical beam components propagate at an angle with respect to each other. As illustrated in Figure 27B, the P polarized beam component of beam 367 propagates essentially straight

through element 370 while the S polarized beam component of beam 367 is refracted at an angle relative to the P polarization beam direction as it propagates through element 370. The length of the birefringent crystal element 370 is chosen so that the P polarized beam path 382 exiting the element 370 is spatially separated from the S polarized beam path 384 exiting the element 370, as illustrated in Figure 27B.

The beam paths 382 and 384 are parallel and spatially separated as they propagate through grating element 10 and dihedral mirror element 374. As illustrated in Figure 27B, the dihedral mirror element 374 has a 90 degree angle between its reflecting mirror surfaces and, thereby, functions as a retroreflecting mirror element that redirects the beam propagating from element 10 to element 374 along beam path 382 to propagate back to element 10 along beam path 384 while redirecting the beam that propagates from element 10 to element 374 along beam path 384 to propagate back to element 10 along beam path 382. Positioned in beam path 382, but not in beam path 384, is halfwave retardation plate 372 that converts the polarization direction of the oppositely propagating beams in beam path 382 from P polarization to S polarization for the beam propagating from element 370 to element 10 and from S polarization to P polarization for the beam propagating from element 10 to element 370. The birefringent crystal element 370 functions in a reversible manner and, thereby, recombines the beams propagating in beam paths 382 and 384 that are incident to element 370 into a single beam 376 that propagates from element 370 to lens 368.

For the optical arrangement illustrated in Figure 27B, the beams propagating in either direction of beam paths 282 or 284 that are incident on grating element 10 are S polarized and, therefore, have equal diffraction efficiency values which enables the device 360 to achieve radiometric throughput efficiency values for S and P polarized optical components that are equal to within about 5 percent of each other. The diffraction grating and dihedral mirror arrangement in device 360 functions as a dual pass cascaded grating arrangement, as described for the dual pass grating device 130 of Figure 7. The wavelength dispersion power of device 360 is equal to approximately twice the value of the wavelength dispersion power of grating element 10 used in the device. The angular separation between the different wavelength channel beams exiting element 370 of device 360 are calculated using Equation (4). The λ/D value for the grating element 10 in device 360 is effectively doubled. Therefore, device 360 can be fabricated with an effective λ/D ratio value of about

1.6 to 4.0 and still achieve essentially equal radiometric throughput efficiency for values for S and P polarized optical components, that is, having values within about 5 percent of each other.

A schematic side view is illustrated in Figure 28 of a grating and mirror arrangement that enables the device 390 of this figure to achieve essentially equal radiometric throughput efficiency values for S and P optical polarization components while using a surface-relief transmission grating element 10 having a λ/D value of about 1.4142. As depicted in Figure 28, the incident beam 367 to device 390 is composed of both S and P polarized optical components where the S component 378 is depicted as an ellipse with a dot at its center while the P component 380 is depicted as a bold arrow. Only the S and P polarized components to the left of grating element 10 are labeled with their respective numbers 378 and 380. Though it may appear that the polarization direction convention used in Figure 28 is opposite to that used in Figure 27B, they are the same since Figure 28 provides a side view relative to grating element 10 while Figure 27B provides a top view relative to grating element 10.

Incident beam 367 of device 390 makes an angle of 45 degrees with respect to the normal of the surface of grating element 10 and, therefore, if it is assumed that grating element 10 of device 390 has a λ/D value of about 1.4142 and a grating aspect ratio in the range of 1.3 to 2.0, then according to the data in Figure 4 the following diffraction conditions occur, which are depicted in Figure 28. Grating element 10 diffracts essentially 100 percent of the S polarized beam component of the incident beam 367 while passing through undiffracted essentially 100 percent of the P polarized beam component of beam 367. For these diffraction conditions, grating element 10 performs the same function as the birefringent crystal element 370 of Figures 27A and 27B in that grating element 10 functions as a polarization beam splitter element. Combining the polarization beam splitter function into grating element 10 improves device performance with regard to optical insertion loss and wavefront errors, as well as device cost, relative to the device 360 arrangement in Figures 27A and 27B which incorporates a polarization beam splitter element based on a birefringent crystal component. Also, grating element 10 in device 390 can have essentially half the width used for the grating element in device 360 in Figures 27A and 27B since the beam propagating through element 10 in device 390 are collinear versus the spatial separated arrangement in device 360.

Both the diffracted and undiffracted beams in device 390 make an angle of 45 degrees to the normal to the grating surface of element 10. The S polarized diffracted beam propagates along beam path 382 of device 390 until beam fold mirror element 122 redirects it along beam path 386 in a counterclockwise direction. The P polarized undiffracted beam propagates along beam path 384 of device 390 until beam fold mirror element 122' redirects it along beam path 386 in a clockwise direction. Halfwave retardation plate 372 positioned in beam path 386 converts the polarization direction of the oppositely propagating beams in beam path 386 from P polarization to S polarization for the clockwise propagating beam and from S polarization to P polarization for the counterclockwise propagating beam. The counterclockwise propagating P polarized beam in beam path 386 is redirected by beam fold mirror element 122' along beam path 384 while the clockwise propagating S polarized beam in beam path 386 is redirected by beam fold mirror element 122 along beam path 382.

Grating element 10 functions in a reversible manner and, therefore, element 10 diffracts essentially 100 percent of the clockwise propagating S polarized beam in beam path 382 while passing through undiffracted essentially 100 percent of the counterclockwise propagating P polarized beam in beam path 384. Both of these diffracted and undiffracted beams propagate back along the incident beam path 367 as beam 367. Because grating element 10 functions in a reversible manner, the S and P polarized optical components of beam 367 have essentially equal values, thereby enabling device 390 to have essentially equal radiometric efficiency values for S and P polarizations.

It should be noted that while the S and P polarized components of the incident beam 367 pass twice through grating element 10 of device 390, each of these polarization components is only diffracted once by element 10 and, therefore, device 390 has a wavelength dispersion power as measured by its effective λ/D value that is just equal to that of grating element 10, which for the example depicted in Figure 28 corresponds to a λ/D value of about 1.4142. The polarization beam splitter function depicted for grating element 10 in device 390 can be achieved for surface-relief transmission gratings having a λ/D value of about 1.4142 to approximately 2.0 and, therefore, the effective λ/D value for device 390 can be from about 1.4142 to approximately 20 while achieving essentially equal radiometric throughput efficiency values for the S and P polarization components.

A major objective when designing grating-based devices for fiber-optic communication system applications is to incorporate techniques in the design for passively athermalizing the performance of the devices so that they meet operating specifications when used over the 70 degree centigrade temperature range specified for fiber-optic telecommunication applications without the need for active control. One of the major factors in these design techniques is to fabricate the surface-relief transmission grating element on a low thermal expansion substrate material because the thermal expansion coefficient of the substrate material determines how rapidly the grating line spacing changes as a function of temperature change for surface-relief gratings having a grating forming layer thickness that is extremely small in comparison to the substrate thickness. Change in the grating line spacing of a grating element causes a corresponding change in the angle of the beam diffracted by the element, which results in a positional change of the focused diffracted beam at the focal plane of the Mux/Demux, wavelength channel monitoring or ADWM device incorporating the grating element. These changes in focused beam position give rise to increased optical insertion loss in the device and if large enough cause a shifting of data information between adjacent wavelength channels in the device.

An optical wavelength selection apparatus containing a surface-relief transmission diffraction grating, a collimating lens for collimating a beam incident to the diffraction grating, and a focusing lens for focusing the beams diffracted by the diffraction grating. The diffraction grating, after having been subjected to a test condition of 85 degrees centigrade and a relative humidity of 85 percent for at least 500 hours, has diffraction efficiency performance within 6 percent of that achieved before being subjected to these test conditions.

An optical wavelength selection apparatus containing a surface-relief transmission diffraction grating, a collimating lens for collimating a beam incident to the diffraction grating, and a focusing lens for focusing the beams diffracted by the diffraction grating. The diffraction grating, after having been subjected to a test condition of 85 degrees centigrade and a relative humidity of 85 percent for at least 500 hours, has diffraction efficiency performance within 6 percent of that achieved before being subjected to these test conditions.

While the device examples presented in this specification have focused on different arrangements for using surface-relief transmission grating elements for fabricating Mux/Demux, on-line wavelength channel monitoring and add/drop devices used in WDM

fiber-optic systems, it is evident that these transmission gratings and the different usage arrangements described in this specification can also be used to construct tunable laser sources used in fiber-optic communication systems and to build spectrophotometer instruments used by field and laboratory personnel for measuring the wavelength component properties of WDM fiber-optic systems.

I claim:

1. An optical wavelength selection apparatus comprising a surface-relief transmission diffraction grating assembly, a collimating lens assembly for collimating optical beams to said diffraction grating, and a focusing lens assembly for focusing beams diffracted from said diffraction grating, wherein said surface relief diffraction grating assembly is comprised of a substrate and, bonded to said substrate, a surface-relief transmission diffraction grating, and wherein:

(a) said substrate is optically homogeneous, consists essentially of material which has a coefficient of thermal expansion of from about 2×10^{-5} to about -1×10^{-6} per degree centigrade, has a refractive index of from about 1.4 to about 4.0, and has a transmittance of at least about 70 percent;

(b) said surface-relief transmission diffraction grating is comprised of a grating forming layer and a surface-relief grating formed in said grating forming layer, wherein:

1. said surface-relief grating has a peak-to-trough height of from about 0.5 to about 5.0 microns, and
2. the grating aspect ratio of said peak-to-trough height of said surface-relief grating to said grating line spacing of said surface-relief grating is from about 0.8 to about 2.0;

(c) when the incident optical beam to said surface-relief transmission diffraction grating assembly and a first order diffracted optical beam from said surface-relief transmission diffraction grating assembly have substantially equal angles with respect to the normal to the grating surface of said surface-relief transmission diffraction grating assembly, and

1. when the ratio of the wavelength of the incident optical beam to the grating line spacing is from about 0.8 to about 2.0, said surface-relief transmission diffraction grating assembly has a first diffraction efficiency of at least about 70 percent for the S polarized optical component of said incident optical beam, and
2. when the ratio of the wavelength of the incident optical beam to the grating line spacing is from about 0.8 to about 1.2, said surface-relief transmission diffraction grating assembly has a second diffraction efficiency of at least about 70 percent for the P polarized optical component of said incident optical beam and said second diffraction efficiency has a value that decreases from at least 70 percent when the ratio of the wavelength of the incident optical beam to grating line spacing is abou

1.2 to a value of less than 10 percent when the ratio of the wavelength of the incident optical beam to grating line spacing is from about 1.43 to about 2.0;

(d) after said surface-relief transmission diffraction grating assembly has been subjected to a temperature of 85 degrees centigrade and a relative humidity of 85 percent for 1,000 hours and then tested in accordance with the procedure specified in paragraph (c) to determine a third diffraction efficiency for the S polarized optical component and a fourth diffraction efficiency for the P polarized optical component, said third diffraction efficiency is less than 6 percent different than said first diffraction efficiency, said fourth diffraction efficiency is less than 6 percent different than said second diffraction efficiency;

(e) said surface-relief transmission grating assembly is substantially optically clear; and

(f) after said surface-relief transmission grating assembly has been subjected to a temperature of 85 degrees centigrade and a relative humidity of 85 percent for 1,000 hours, said surface-relief transmission grating assembly is still substantially optically clear.

2. The apparatus as recited in claim 1, wherein said surface-relief grating has a substantially sinusoidal shape.

3. The apparatus as recited in claim 1, wherein said first diffraction efficiency and said second diffraction efficiency are no greater than about 10 percent different from each other when the ratio of the wavelength of the incident beam to grating line spacing is from about 0.8 to 1.2.

4. The apparatus as recited in claim 1, wherein said substrate has a coefficient of thermal expansion from about 6×10^{-7} to about -6×10^{-7} per degree centigrade.

5. The apparatus as recited in claim 1, wherein said substrate has a refractive index of from about 1.43 to about 1.7.

6. The apparatus as recited in claim 1, wherein said surface-relief grating has a grating line spacing of from about 1.11 to about 2 microns.

7. The apparatus as recited in claim 1, wherein said surface-relief grating has a grating aspect ratio of from about 1.3 to about 2.0.

8. The apparatus as recited in claim 1, wherein said surface-relief transmission diffraction grating assembly is optically bonded to a glass block element having at least one flat surface.

9. The optical wavelength selection apparatus as recited in claim 1, wherein said surface-relief transmission diffraction grating assembly is attached to a glass block element having at least one flat surface with an encapsulated air layer existing between said surface-relief grating of said surface-relief transmission diffraction grating assembly and said flat surface of said glass block element to which said surface-relief transmission diffraction grating assembly is attached.

10. The optical wavelength selection apparatus as recited in claim 1, wherein said optical wavelength selection apparatus further comprises a second surface-relief transmission diffraction grating positioned after said surface-relief transmission diffraction grating.

11. The optical wavelength selection apparatus as recited in claim 1, wherein said optical wavelength selection apparatus further comprises a beam folding mirror element.

12. The optical wavelength selection apparatus as recited in claim 1, wherein optical wavelength selection apparatus further comprises a mirror element positioned after said surface-relief transmission diffraction grating and orientated to reflect an optical beam diffracted from said surface-relief transmission diffraction grating back to said surface-relief transmission diffraction grating.

13. The optical wavelength selection apparatus as recited in claim 30, wherein said surface-relief transmission diffraction grating and said mirror element are incorporated in a glass block element

14. The optical wavelength selection apparatus as recited in claim 1, wherein said optical wavelength selection apparatus further comprises a beam expansion prism element.

15. The optical wavelength selection apparatus as recited in claim 1, wherein said optical wavelength selection apparatus further comprises a linearizing prism element.

16. The optical wavelength selection apparatus as recited in claim 1, wherein said optical wavelength selection apparatus further comprises a surface-relief reflection grating element positioned after said surface-relief transmission diffraction grating and orientated to diffract an optical beam diffracted from said surface-relief transmission diffraction grating back to said surface-relief transmission diffraction grating.

17. The optical wavelength selection apparatus as recited in claim 1, wherein said optical wavelength selection apparatus further comprises a second surface-relief transmission

diffraction grating disposed between said surface-relief transmission diffraction grating and said focusing lens assembly.

18. The optical wavelength selection apparatus as recited in claim 1, further comprising:

(a) a birefringent crystal element positioned before said surface-relief transmission diffraction grating for splitting said S polarized optical component from said P polarized optical component for optical beams incident to said surface-relief transmission diffraction grating and for combining said S polarized optical component with said P polarized optical component for optical beams diffracted from said surface-relief transmission diffraction grating,

(b) a halfwave retardation plate positioned before said surface-relief transmission diffraction grating for converting said P polarized optical component incident to said surface-relief transmission diffraction grating to a S polarized optical component that is incident on said surface-relief transmission diffraction grating and for converting said S polarized optical component diffracted from said surface-relief transmission grating to a P polarized optical component, and

(c) a dihedral mirror element positioned after said surface-relief transmission diffraction grating for retroreflecting a first diffracted optical beam and a second diffracted optical beam from said surface-relief transmission diffraction grating back to said surface-relief transmission diffraction grating.

19. An optical wavelength selection apparatus comprising a surface-relief transmission diffraction grating assembly, a collimating lens assembly for collimating optical beams to said diffraction grating, and a focusing lens assembly for focusing beams diffracted from said diffraction grating, wherein said surface relief diffraction grating assembly is comprised of a substrate and, bonded to said substrate, a surface-relief transmission diffraction grating, and wherein:

(a) said substrate is optically homogeneous, consists essentially of material which has a coefficient of thermal expansion of from about 2×10^{-5} to about -1×10^{-6} per degree centigrade, has a refractive index of from about 1.4 to about 4.0, and has a transmittance of at least about 70 percent;

(b) said surface-relief transmission diffraction grating is comprised of a grating forming layer and a surface-relief grating formed in said grating forming layer, wherein:

1. said surface-relief grating has a peak-to-trough height of from about 0.5 to about 5.0 microns, and
2. the grating aspect ratio of said peak-to-trough height of said surface-relief grating to said grating line spacing of said surface-relief grating is from about 0.8 to about 2.0;

(c) when the incident optical beam to said surface-relief transmission diffraction grating assembly and a first order diffracted optical beam from said surface-relief transmission diffraction grating assembly have substantially equal angles with respect to the normal to the grating surface of said surface-relief transmission diffraction grating assembly, and

1. when the ratio of the wavelength of the incident optical beam to the grating line spacing is from about 0.8 to about 2.0, said surface-relief transmission diffraction grating assembly has a first diffraction efficiency of at least about 70 percent for the S polarized optical component of said incident optical beam, and
2. when the ratio of the wavelength of the incident optical beam to the grating line spacing is from about 0.8 to about 1.2, said surface-relief transmission diffraction grating assembly has a second diffraction efficiency of at least about 70 percent for the P polarized optical component of said incident optical beam and said second diffraction efficiency has a value that decreases from at least 70 percent when the ratio of the wavelength of the incident optical beam to grating line spacing is about 1.2 to a value of less than 10 percent when the ratio of the wavelength of the incident optical beam to grating line spacing is from about 1.43 to about 2.0; and

(d) after said surface-relief transmission diffraction grating assembly has been subjected to a temperature of 85 degrees centigrade and a relative humidity of 85 percent for 1,000 hours and then tested in accordance with the procedure specified in paragraph (c) to determine a third diffraction efficiency for the S polarized optical component and a fourth diffraction efficiency for the P polarized optical component, said third diffraction efficiency is less than 6 percent different than said first diffraction efficiency, said fourth diffraction efficiency is less than 6 percent different than said second diffraction efficiency.

20. The optical wavelength selection apparatus as recited in claim 19, wherein said surface-relief grating has a substantially sinusoidal shape.

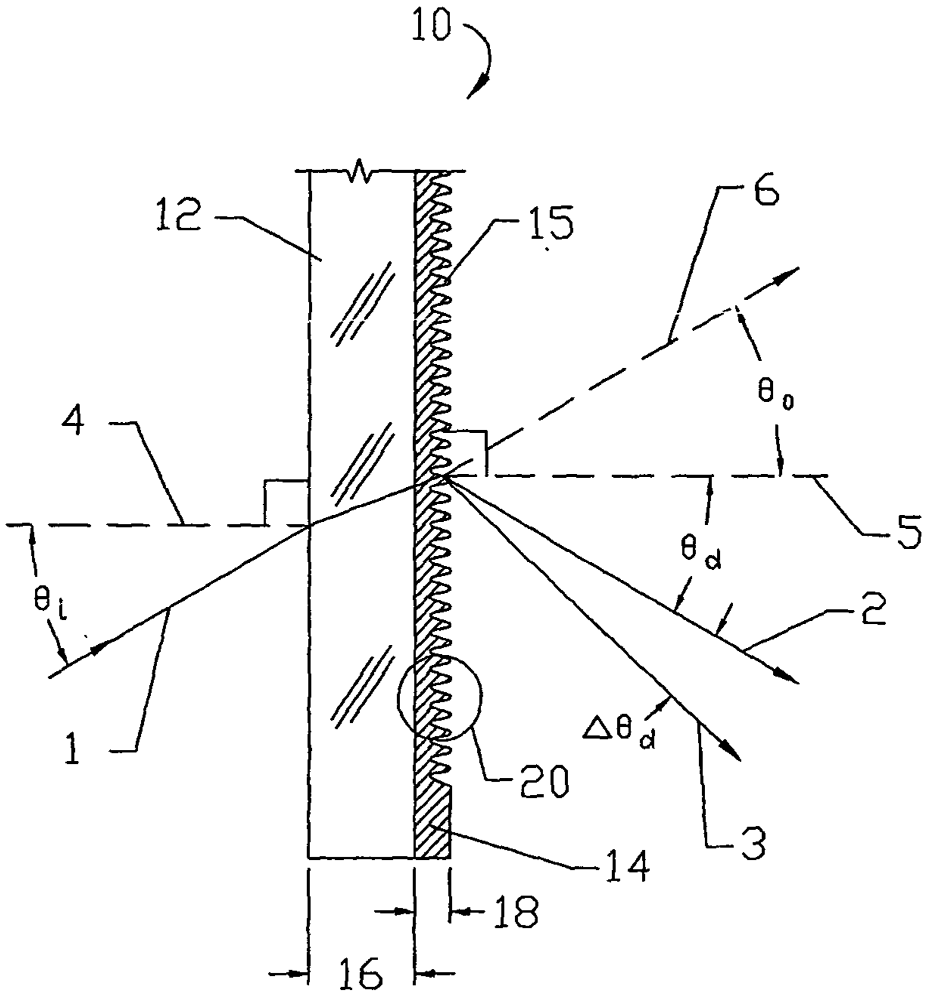

FIGURE 1

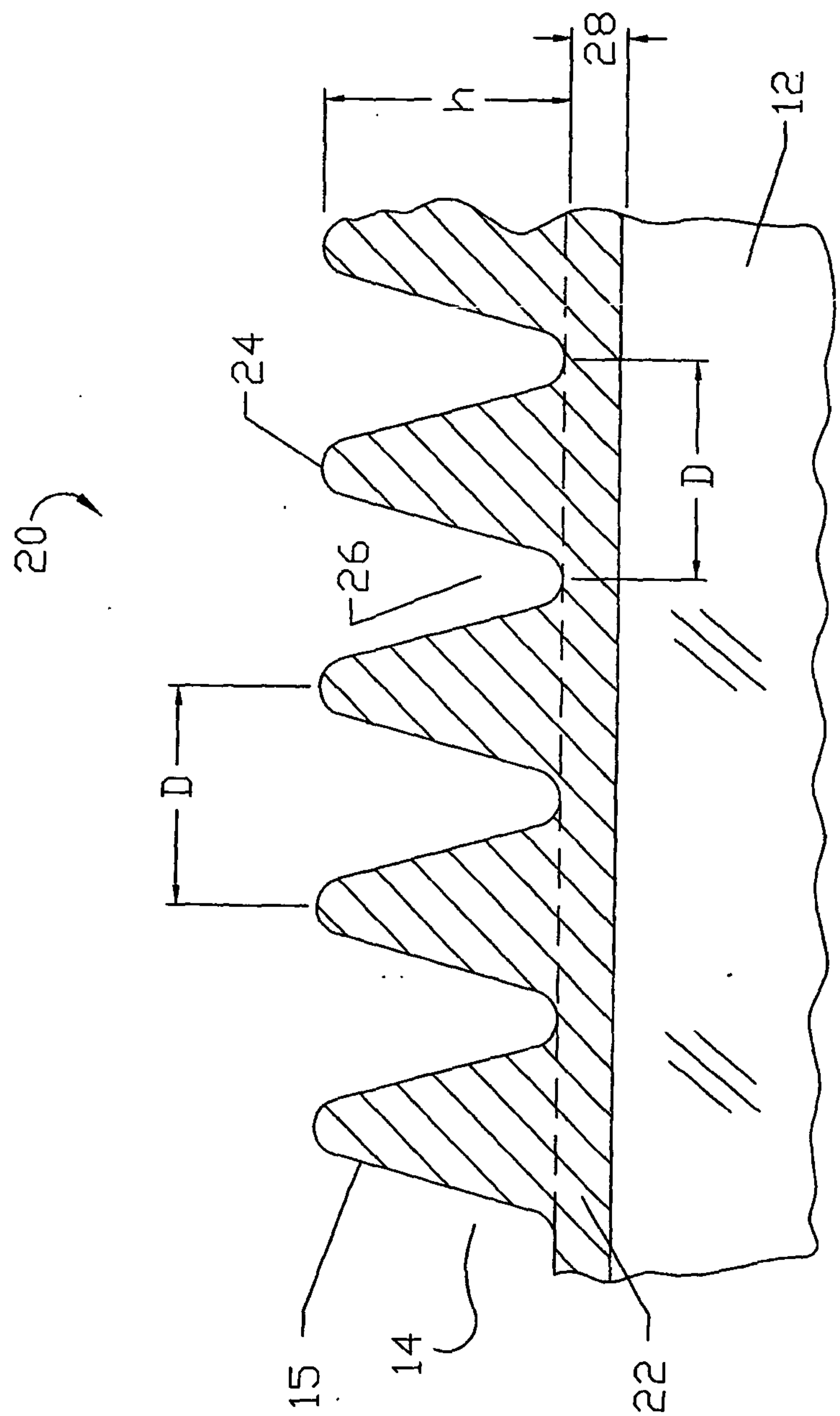

FIGURE 2

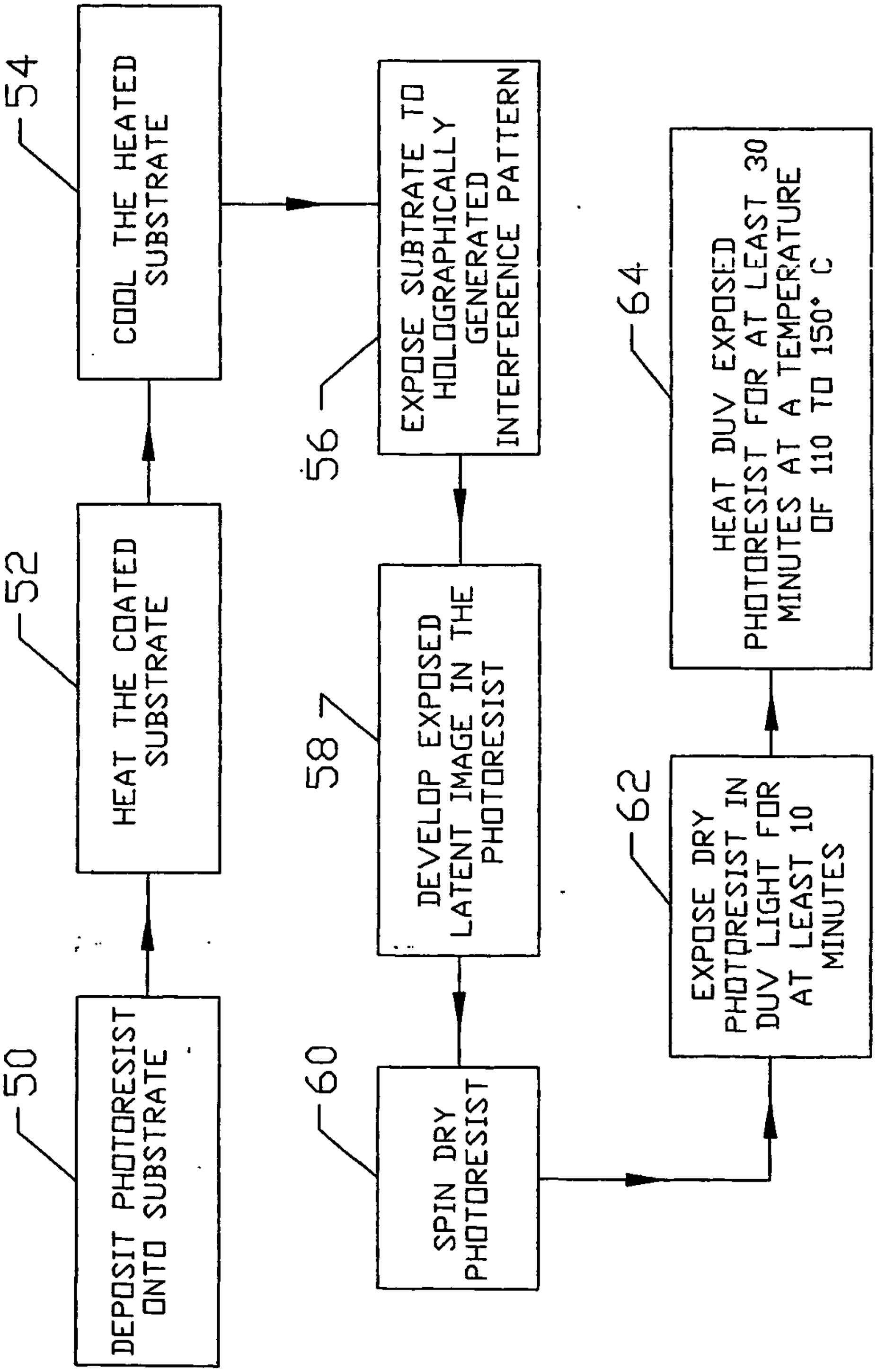
50
DEPOSIT PHOTORESIST ONTO SUBSTRATE
52
HEAT THE COATED SUBSTRATE
54
COOL THE HEATED SUBSTRATE
56
EXPOSE SUBTRATE TO HOLOGRAPHICALLY GENERATED INTERFERENCE PATTERN
58
DEVELOP EXPOSED LATENT IMAGE IN THE PHOTORESIST
60
SPIN DRY PHOTORESIST
62
EXPOSE DRY PHOTORESIST IN DUV LIGHT FOR AT LEAST 10 MINUTES
64
HEAT DUV EXPOSED PHOTORESIST FOR AT LEAST 30 MINUTES AT A TEMPERATURE OF 110 TO 150° C

FIGURE 3

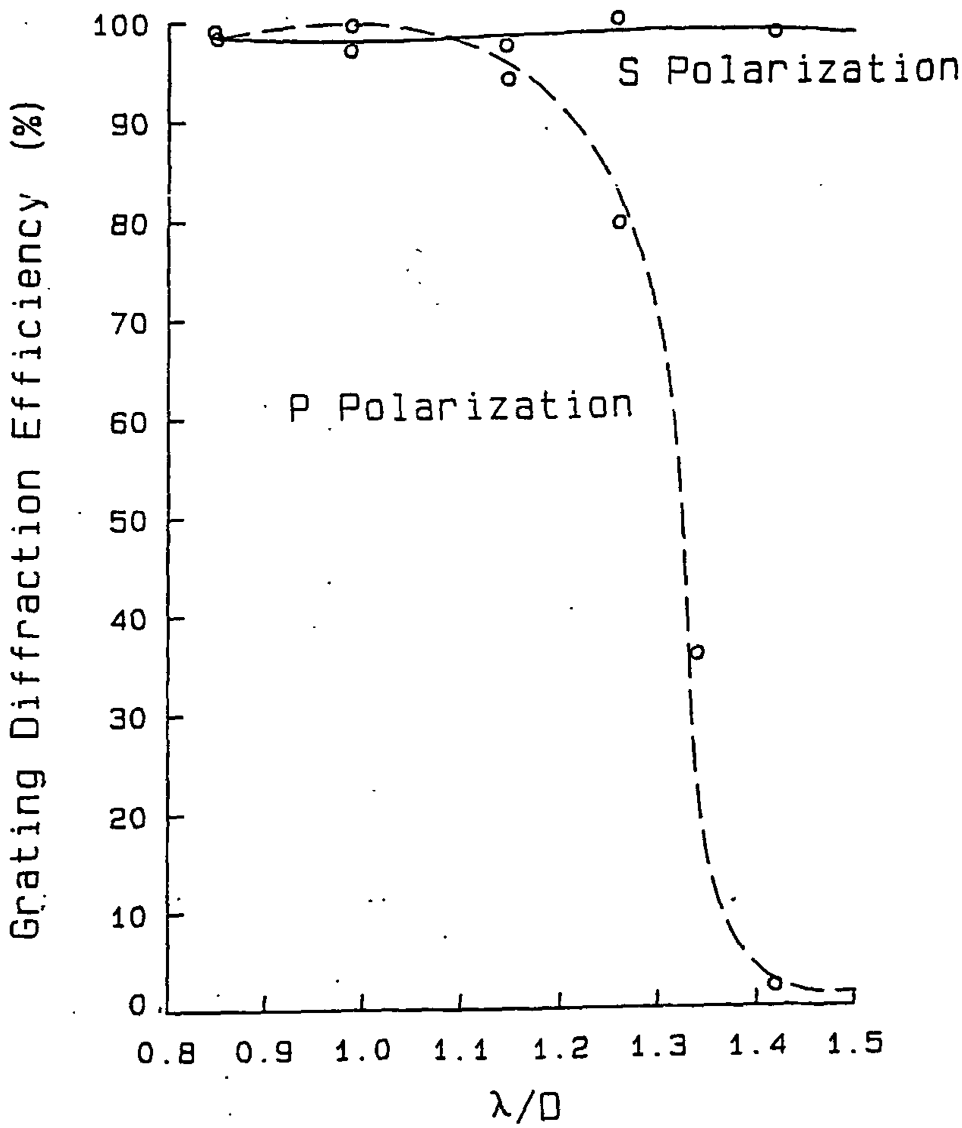
Grating Diffraction Efficiency (%)
100
90
80
70
60
50
40
30
20
10
0
0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5
λ/D
S Polarization
P Polarization

FIGURE 4

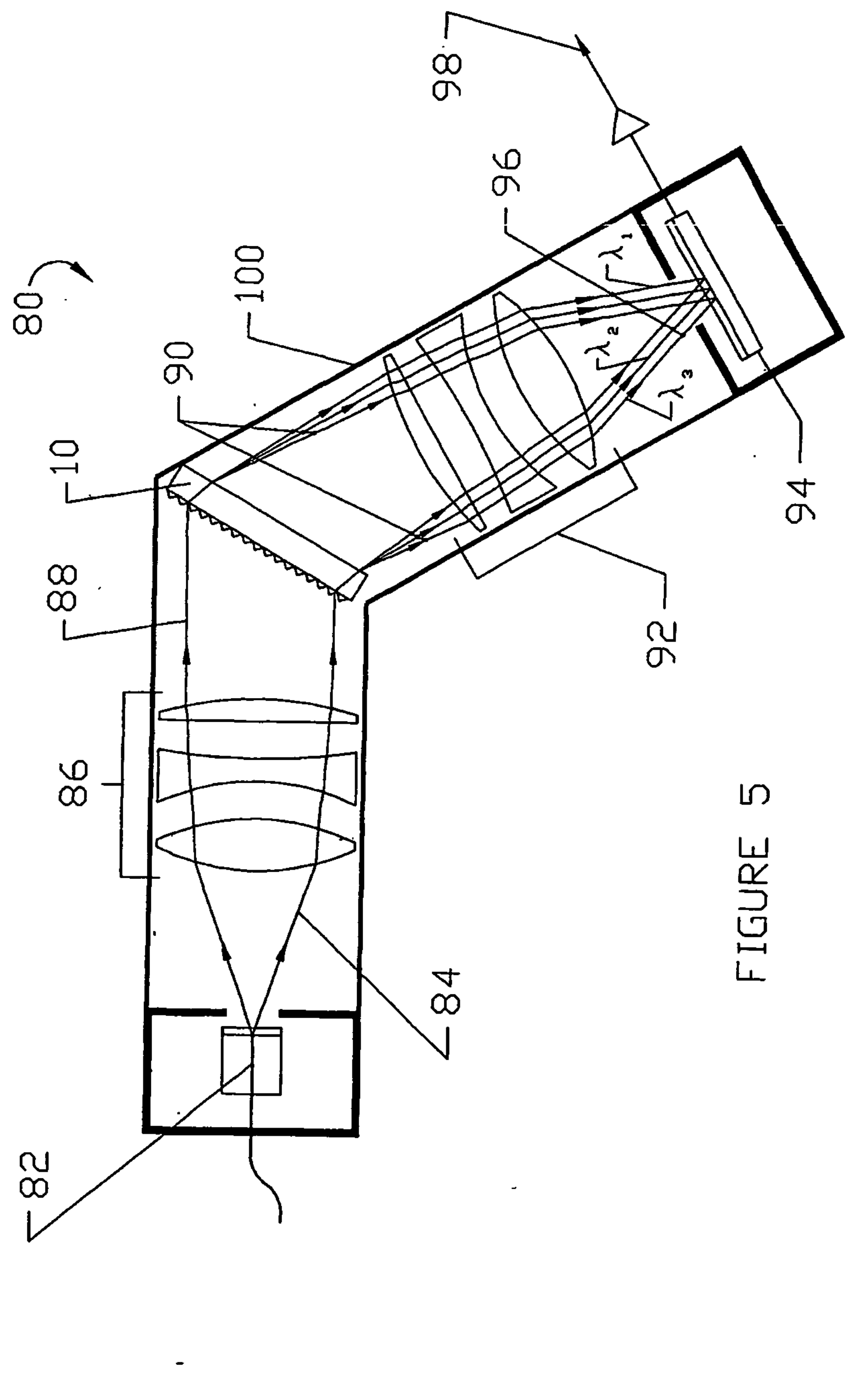

FIGURE 5

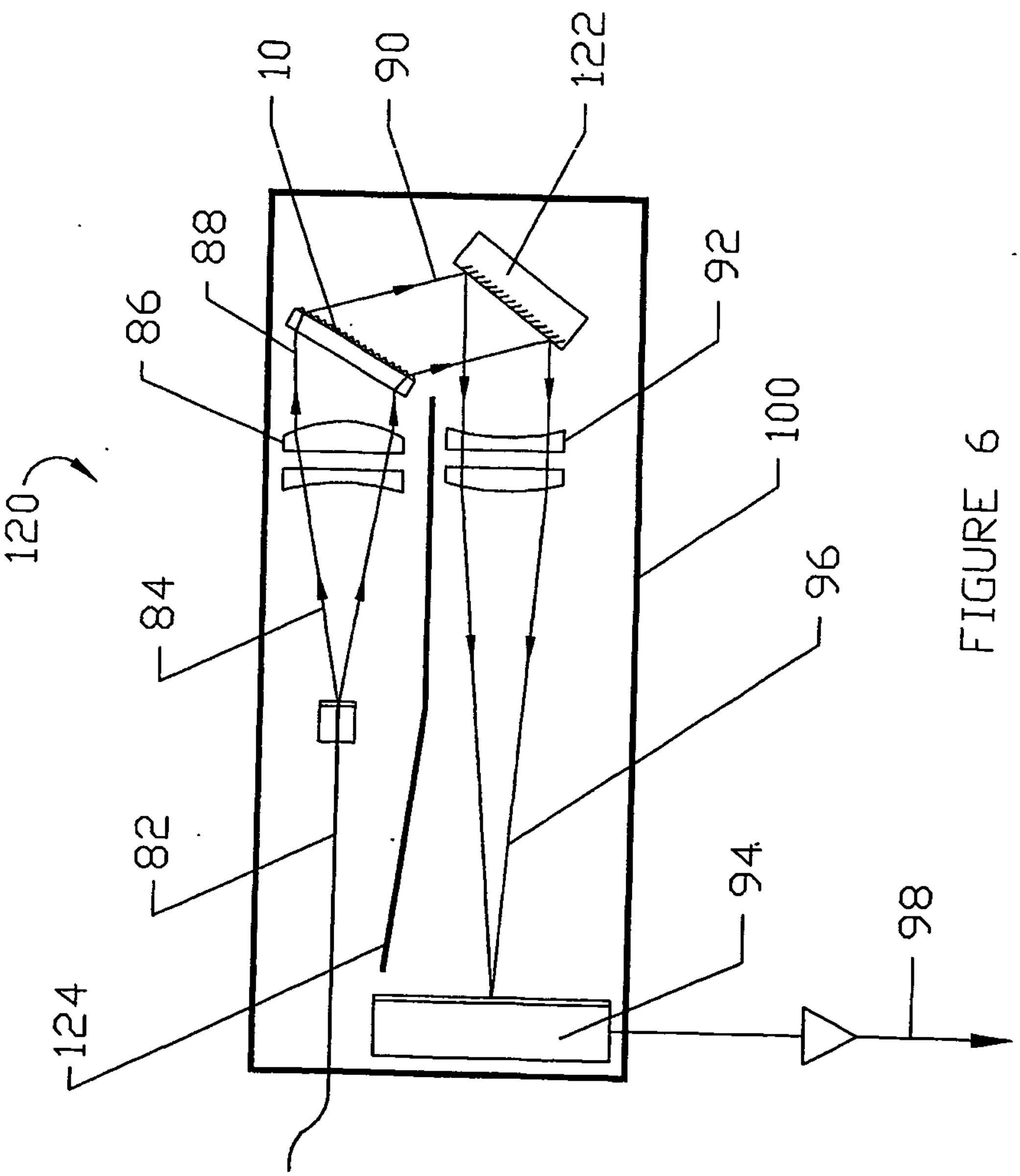

FIGURE 6

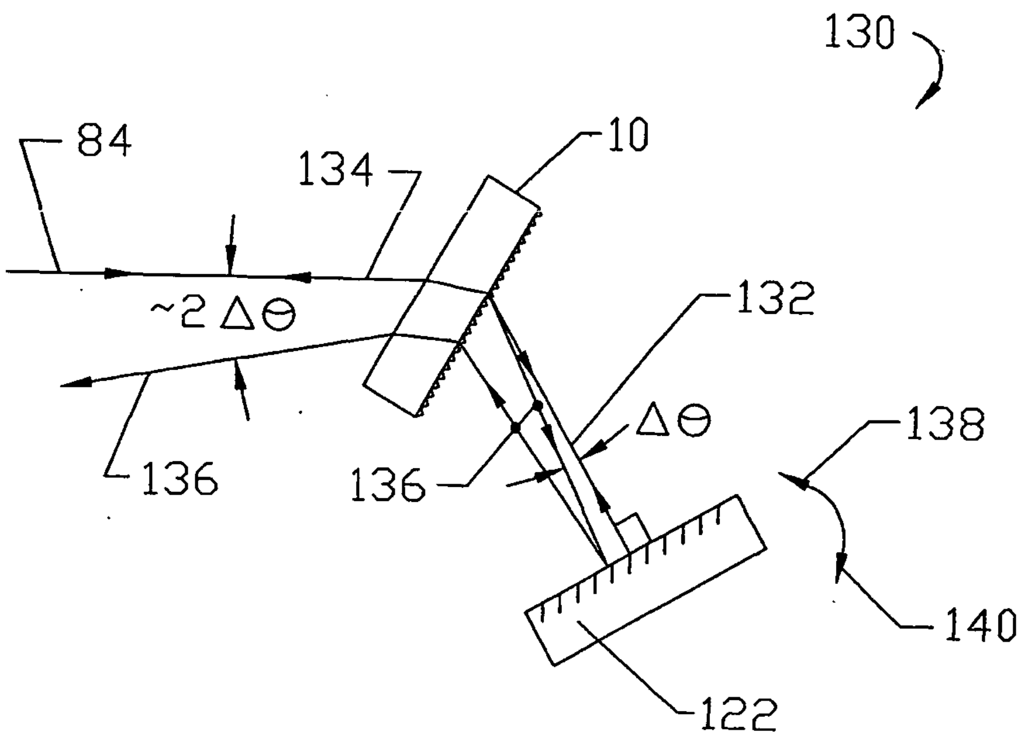

FIGURE 7

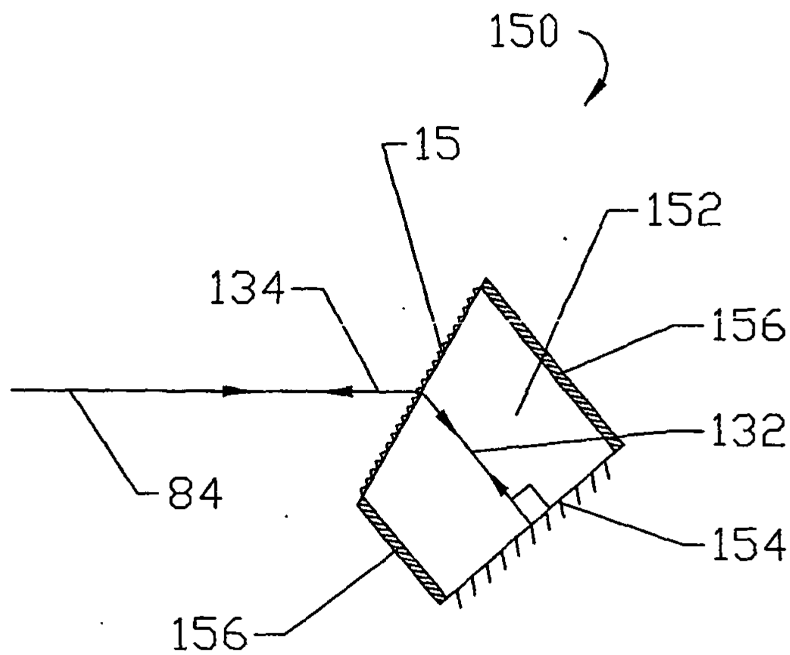

FIGURE 8

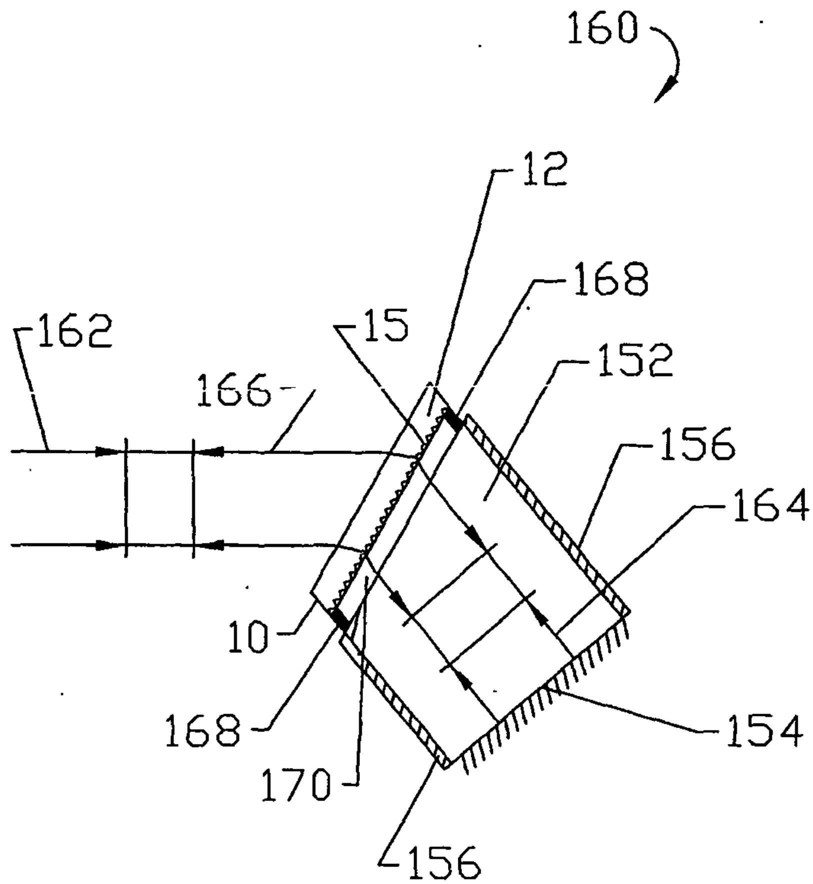

FIGURE 9

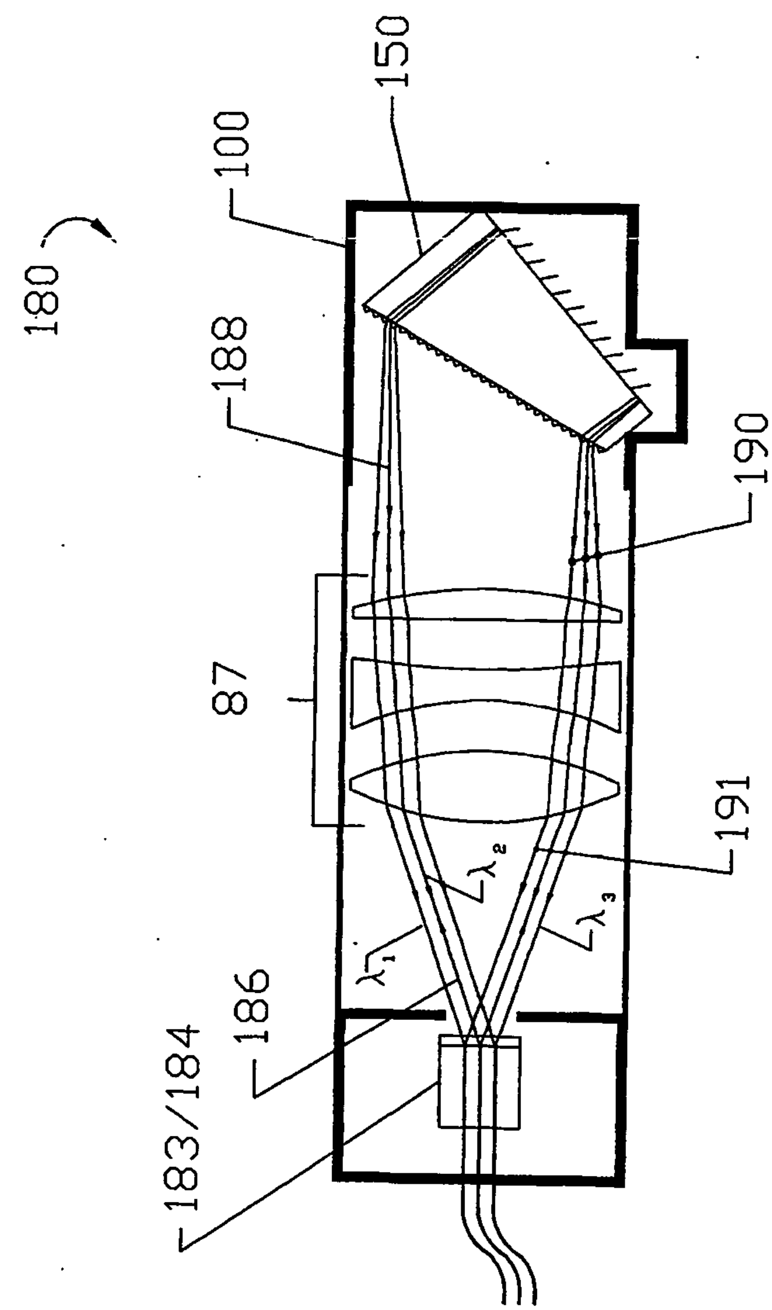
180
100
150
188
190
87
191
186
183/184
λ_1
λ_2
λ_3

FIGURE 10A

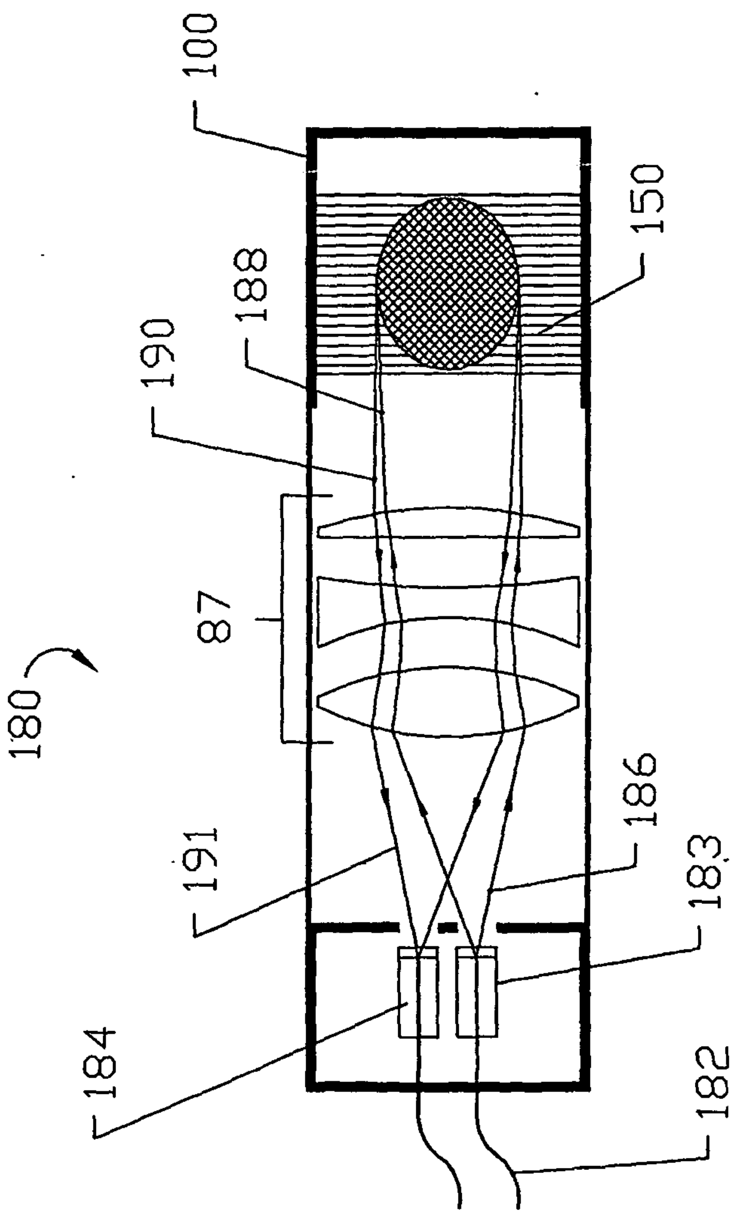

FIGURE 10B

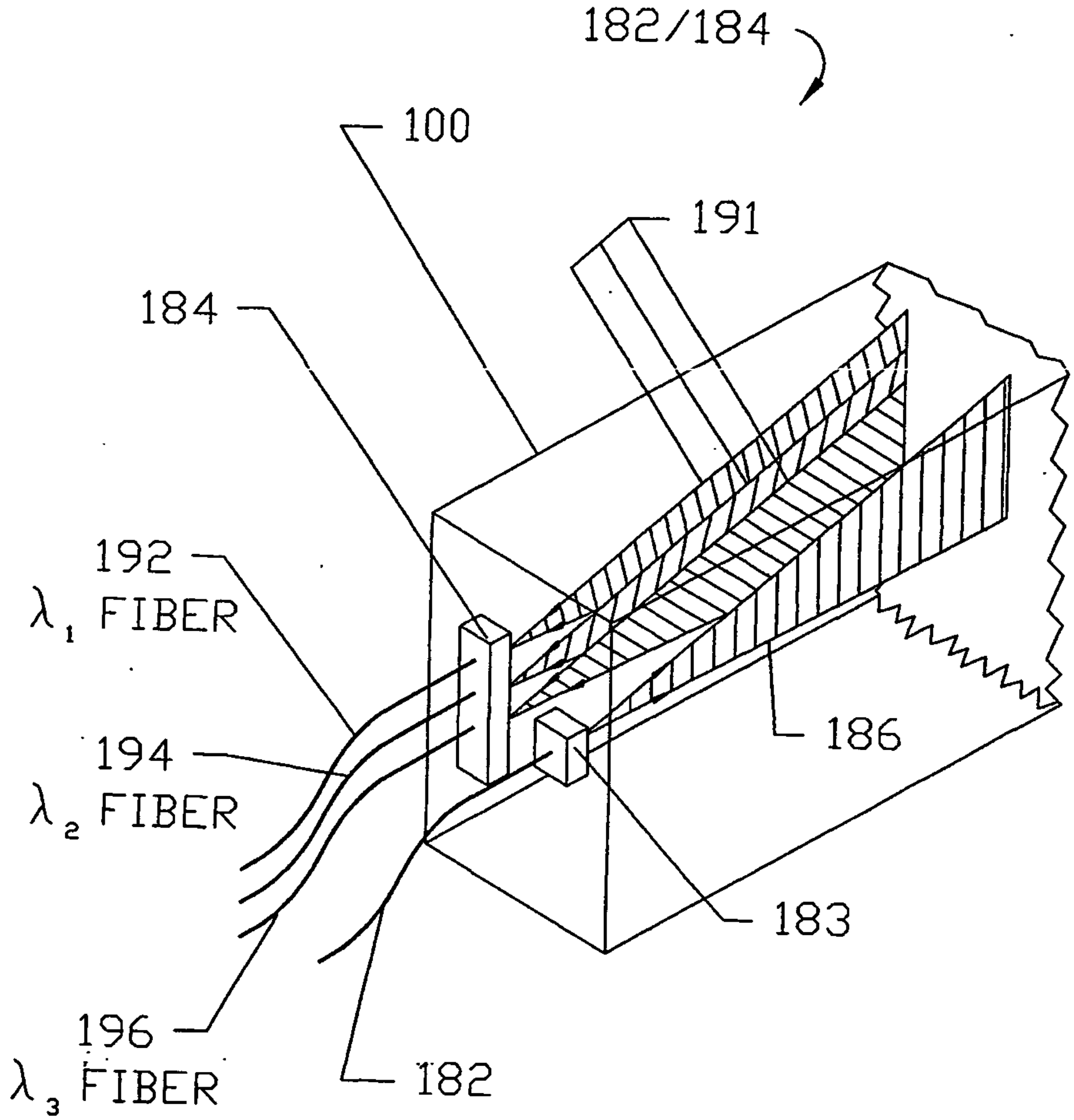
182/184
100
191
184
192
λ_1 FIBER
194
λ_2 FIBER
186
183
196
λ_3 FIBER
182

FIGURE 10C

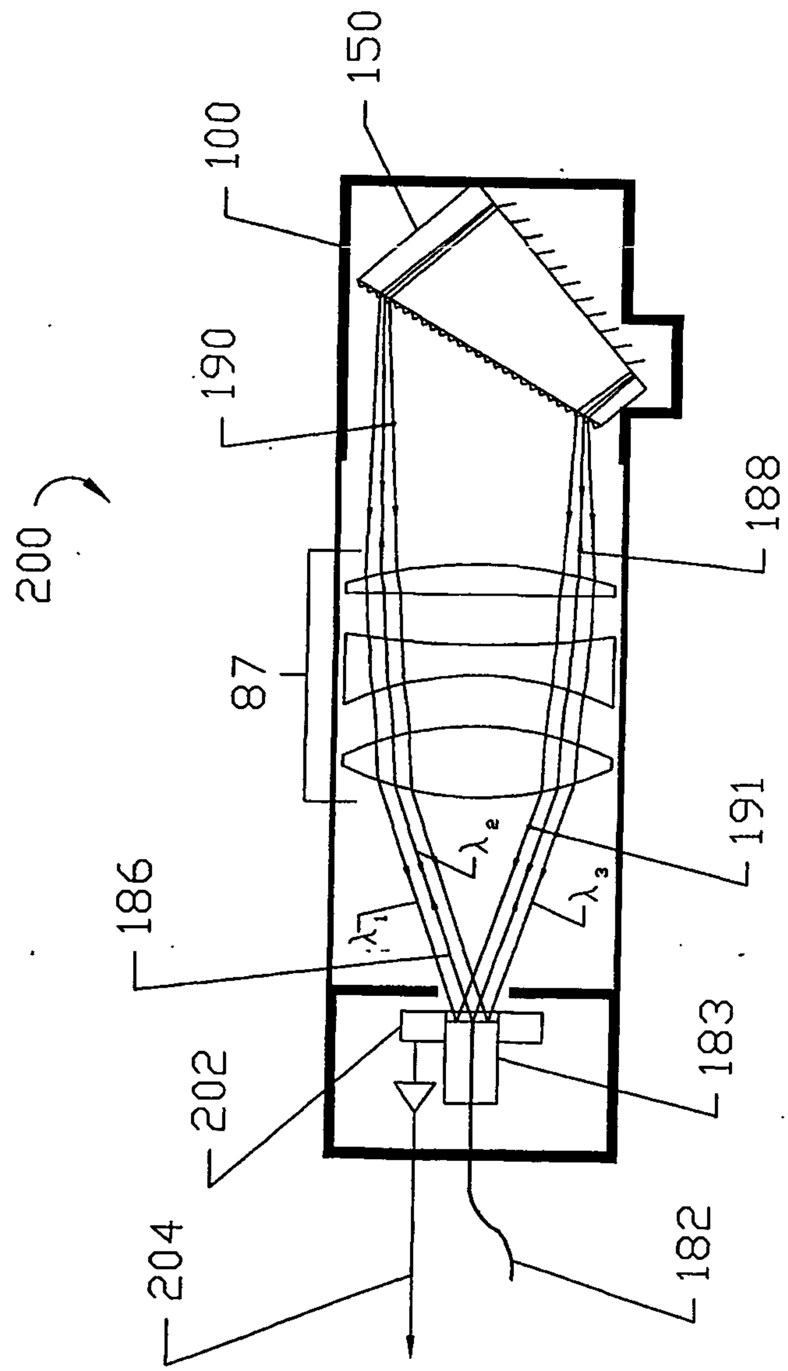

FIGURE 11A

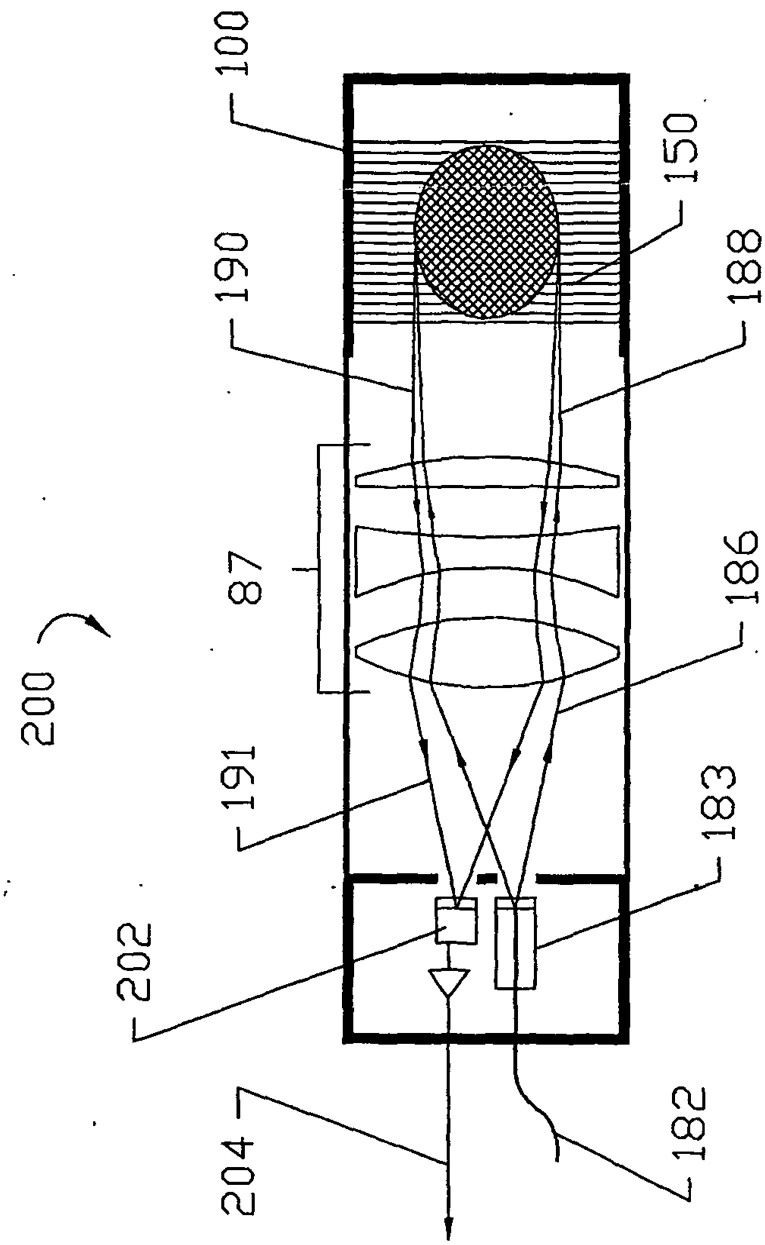

FIGURE 11B

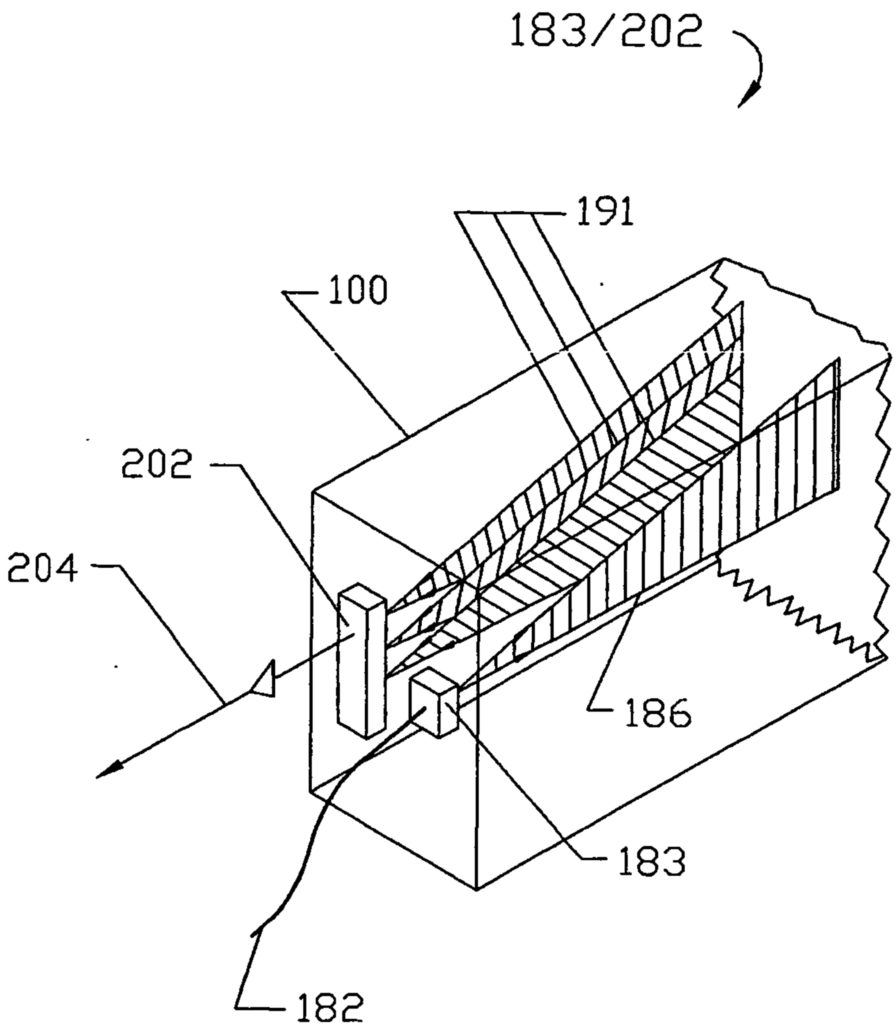

FIGURE 11C

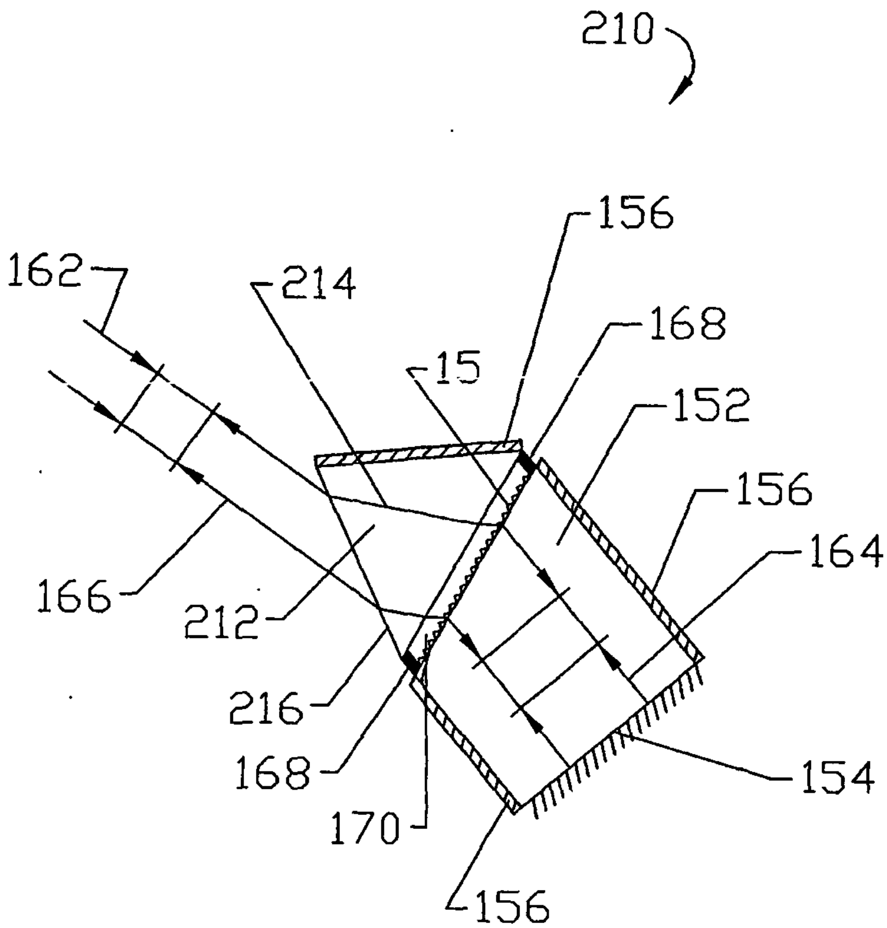

FIGURE 12

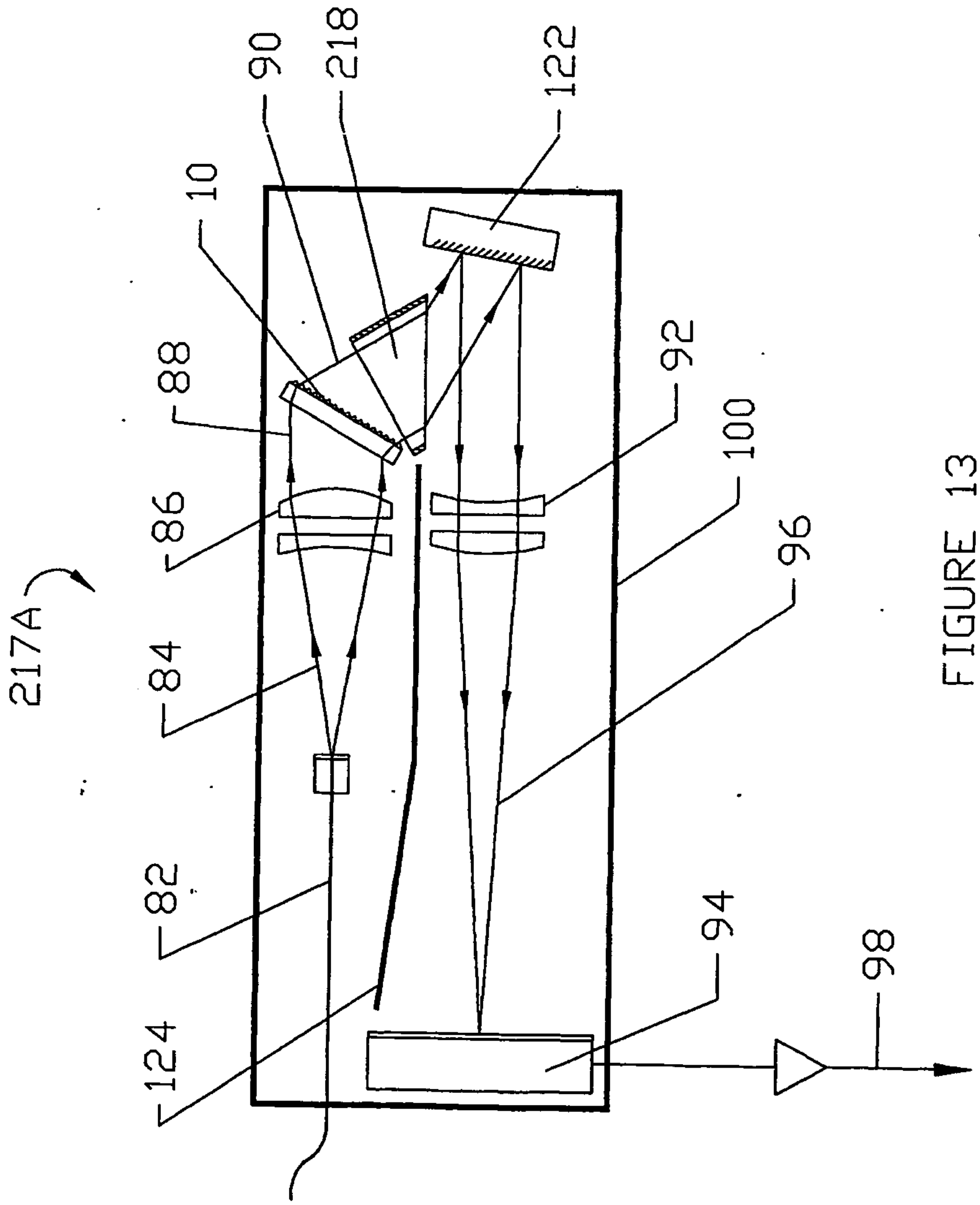

FIGURE 13

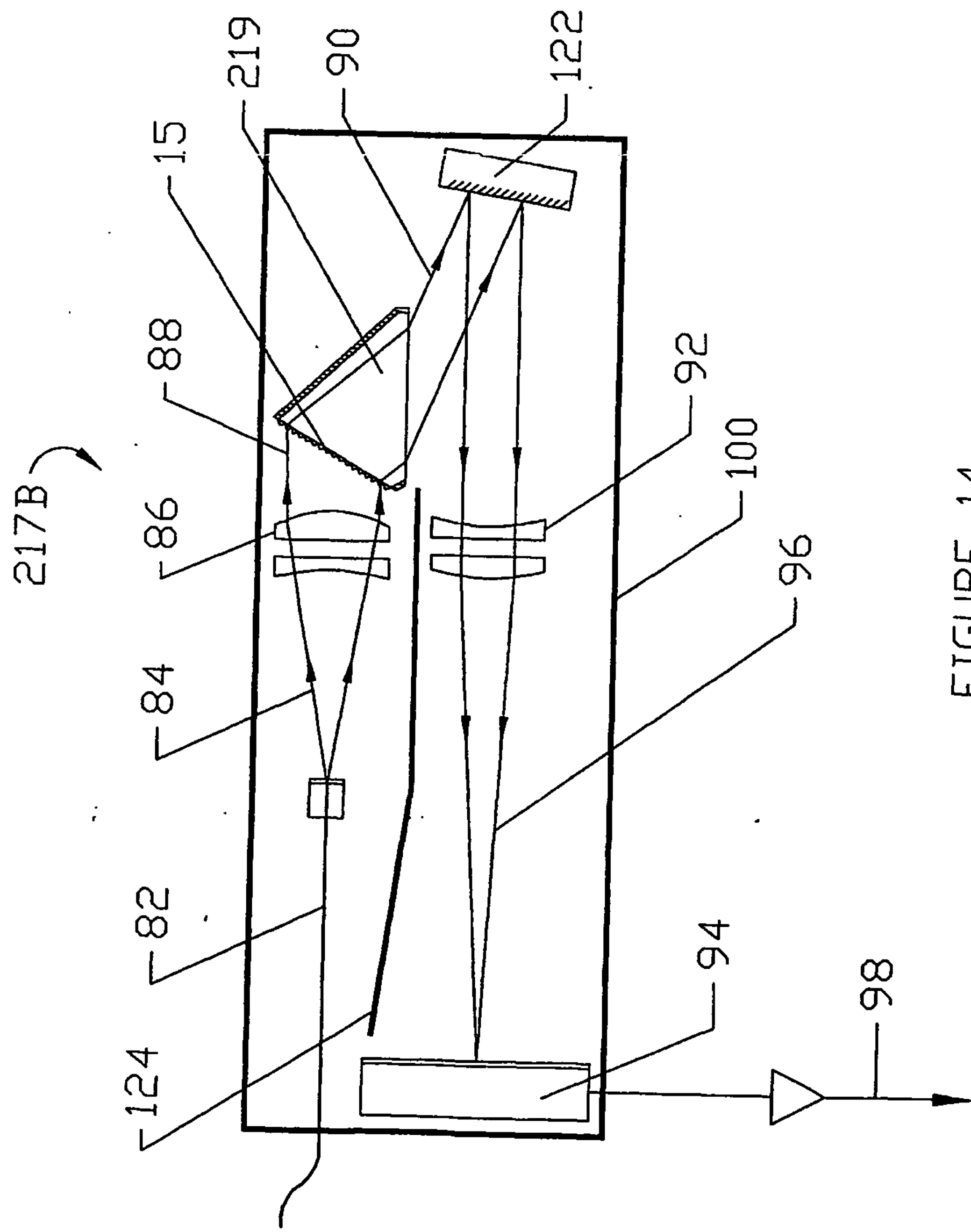

FIGURE 14

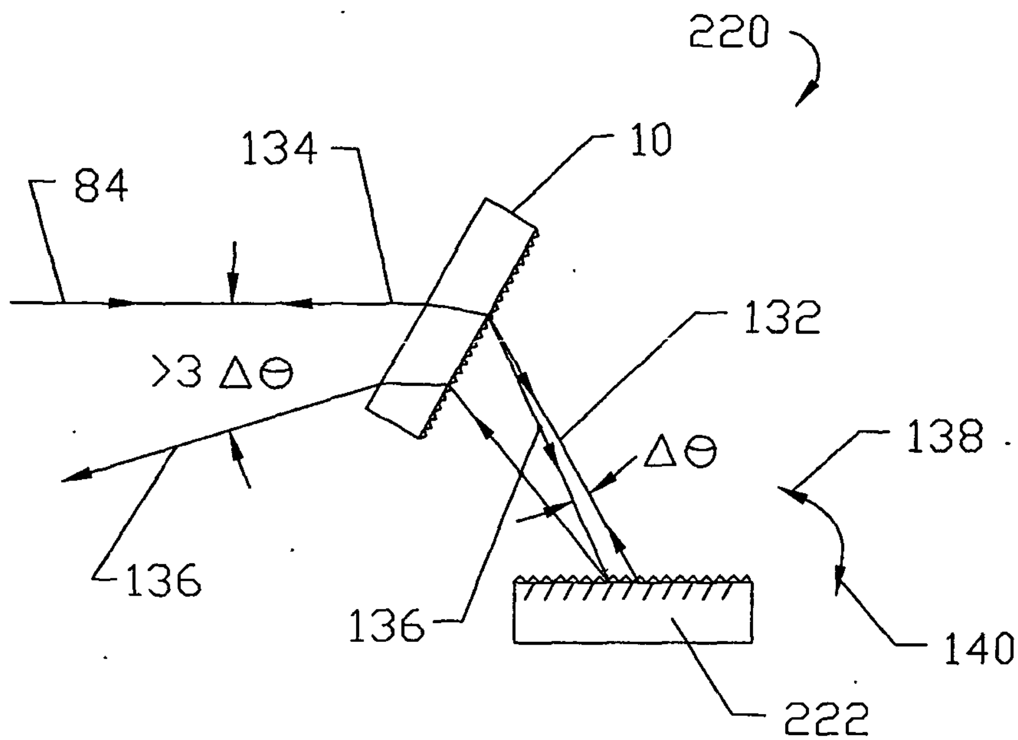

FIGURE 15

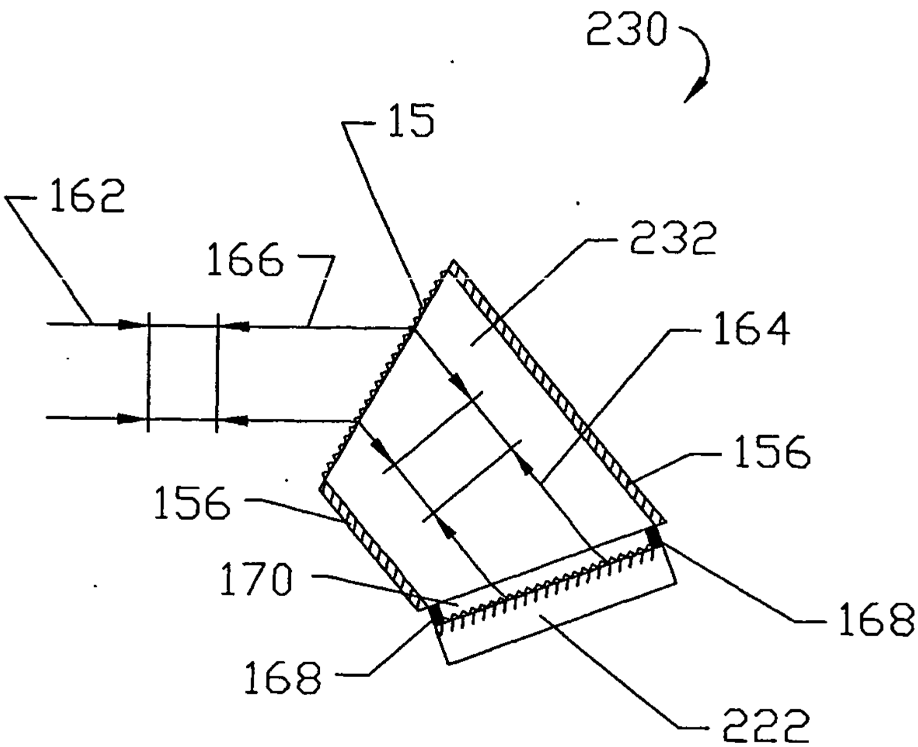

FIGURE 16

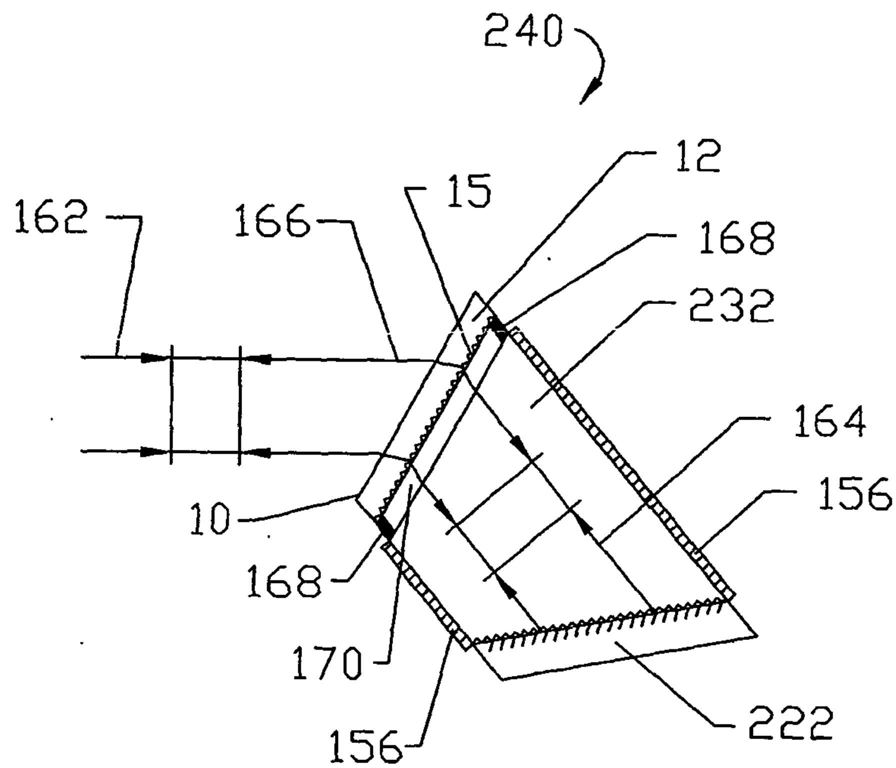

FIGURE 17

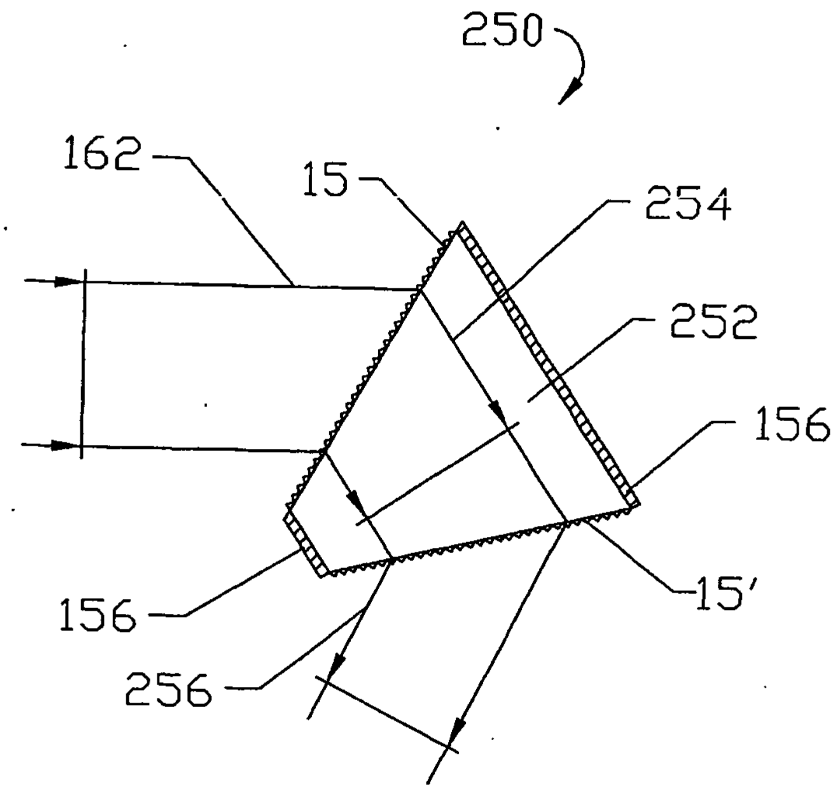

FIGURE 18

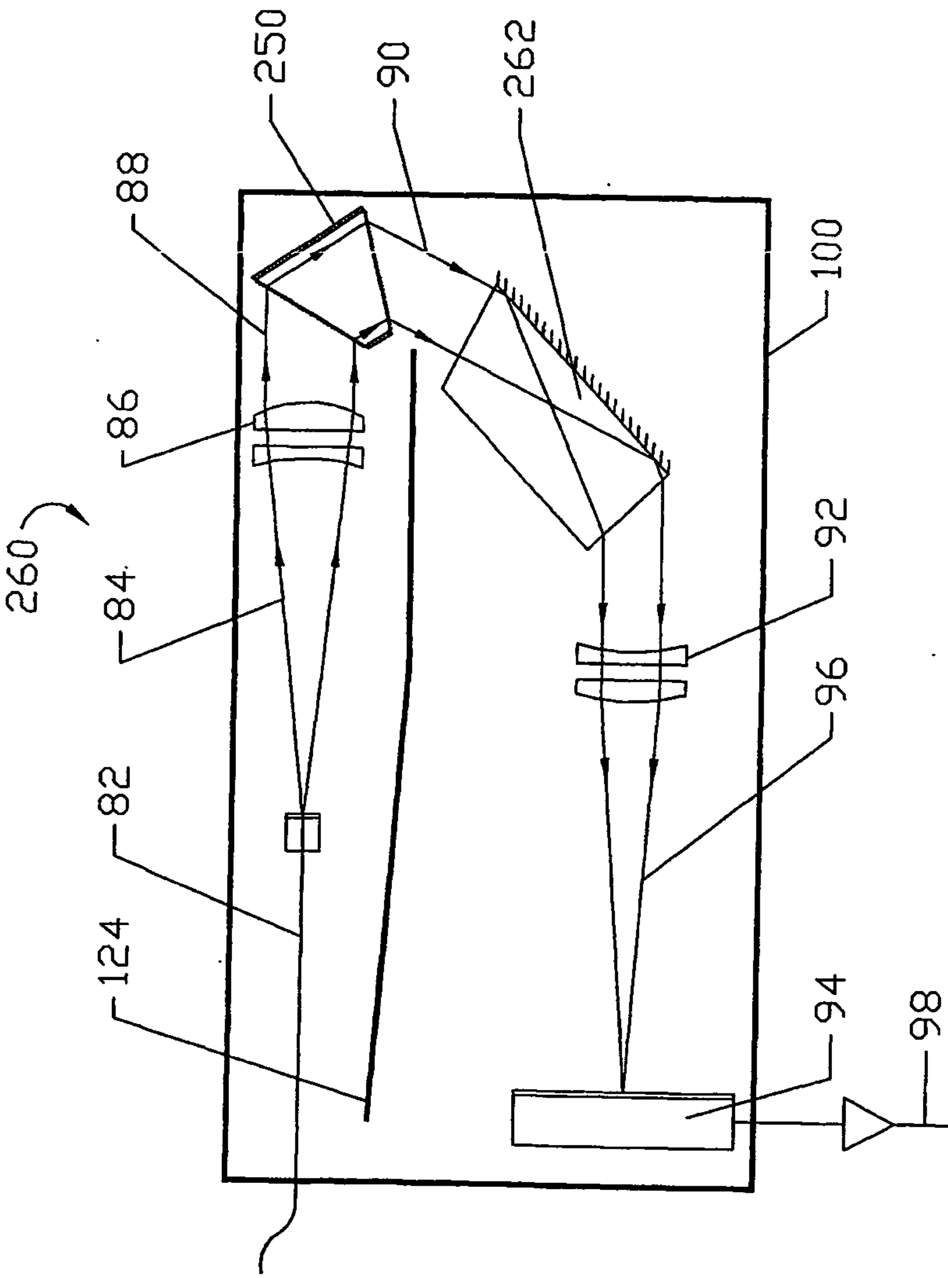

FIGURE 19

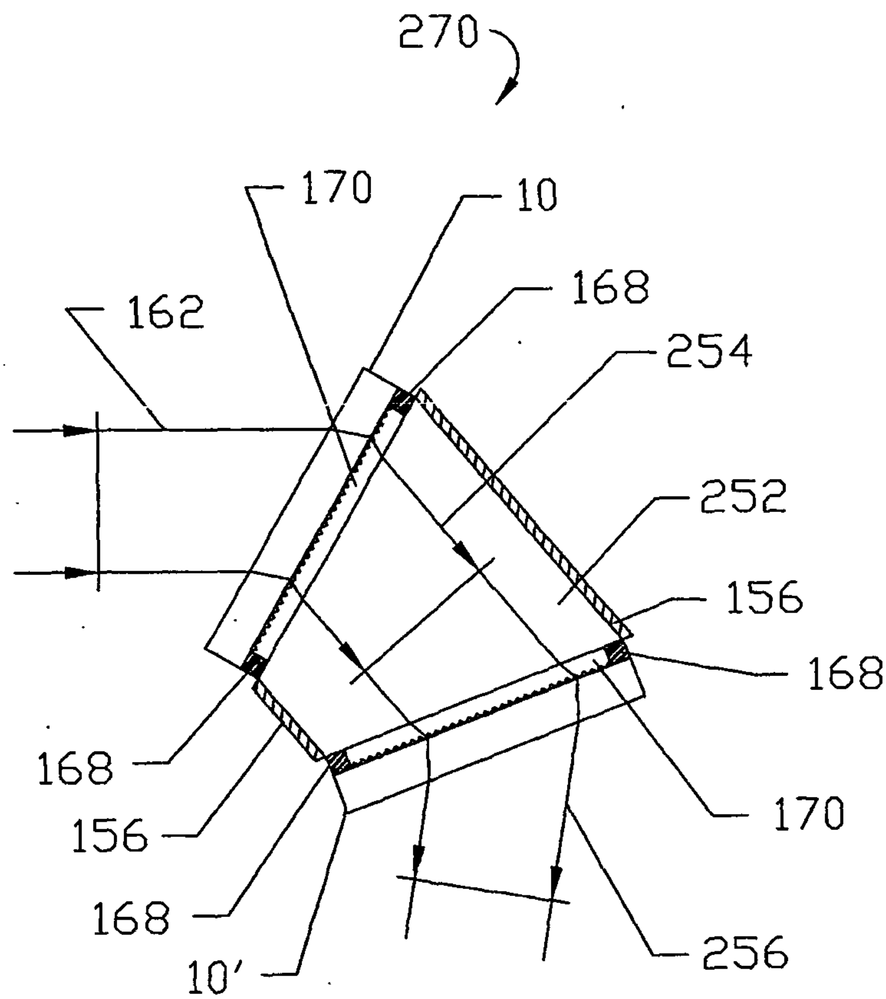

FIGURE 20

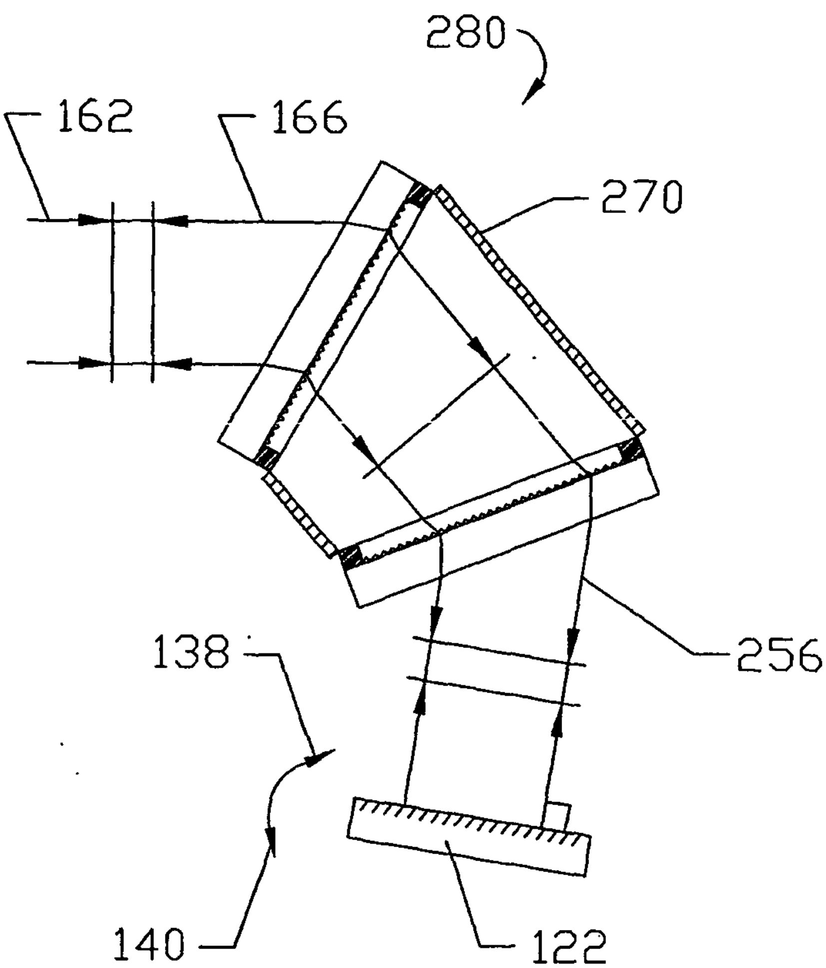

FIGURE 21

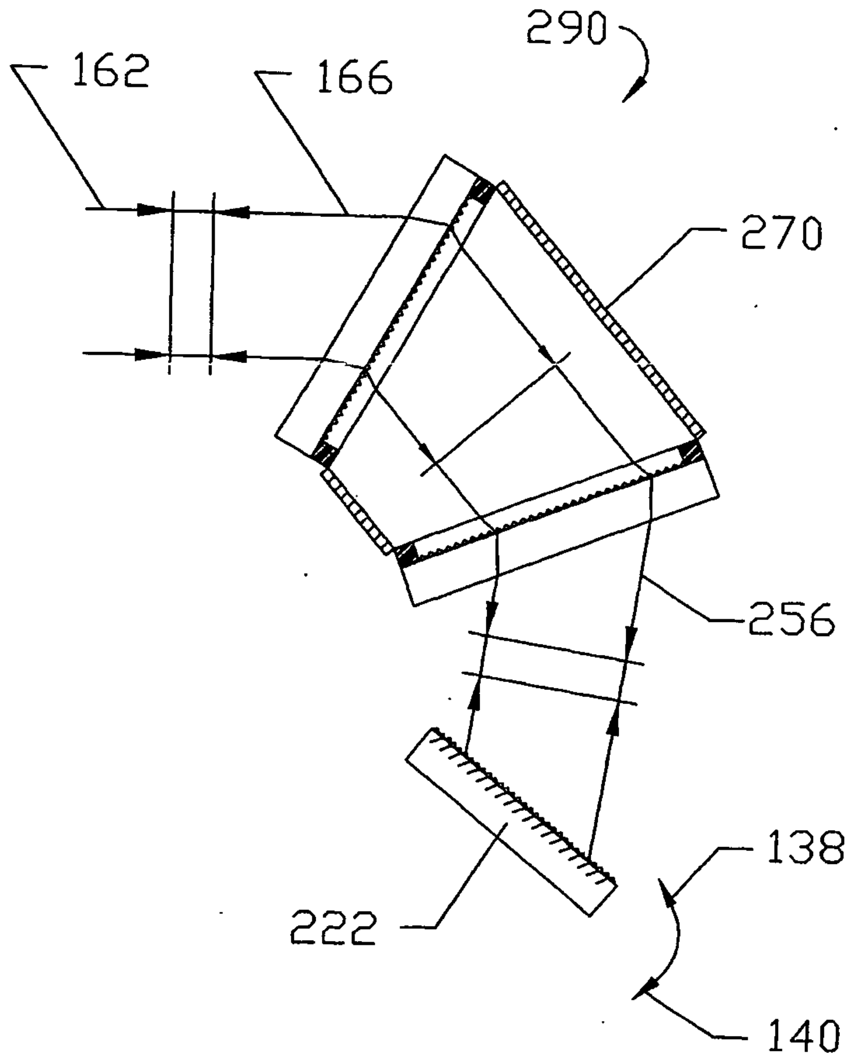

FIGURE 22

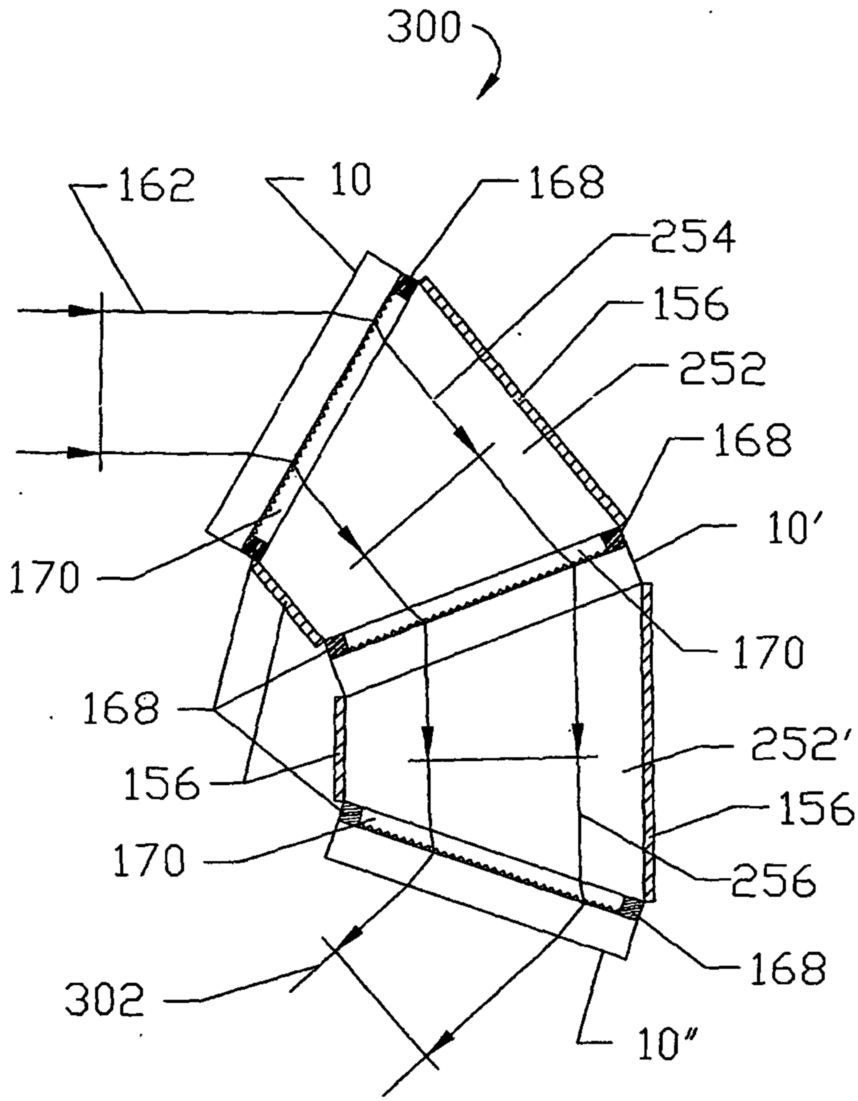
300
162
10
168
254
156
252
168
10'
170
170
168
252'
156
156
170
256
168
302
10"

FIGURE 23

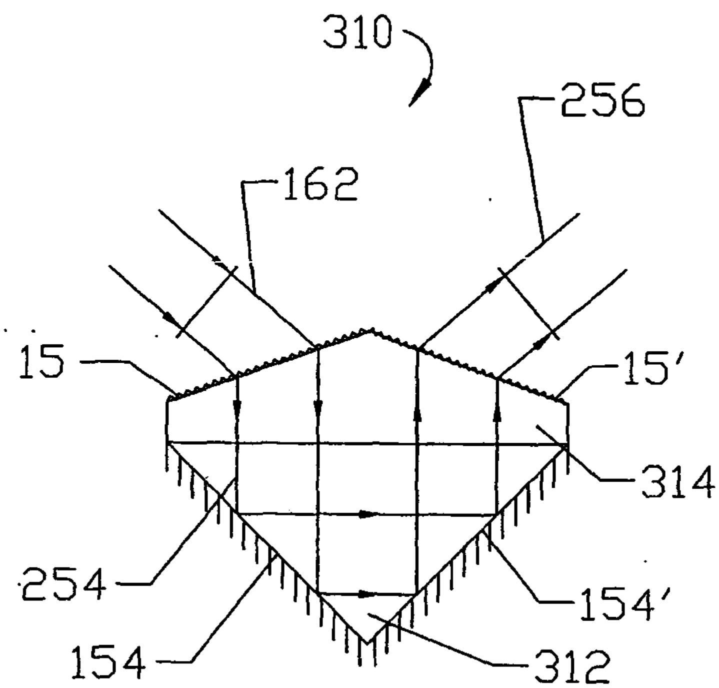

FIGURE 24

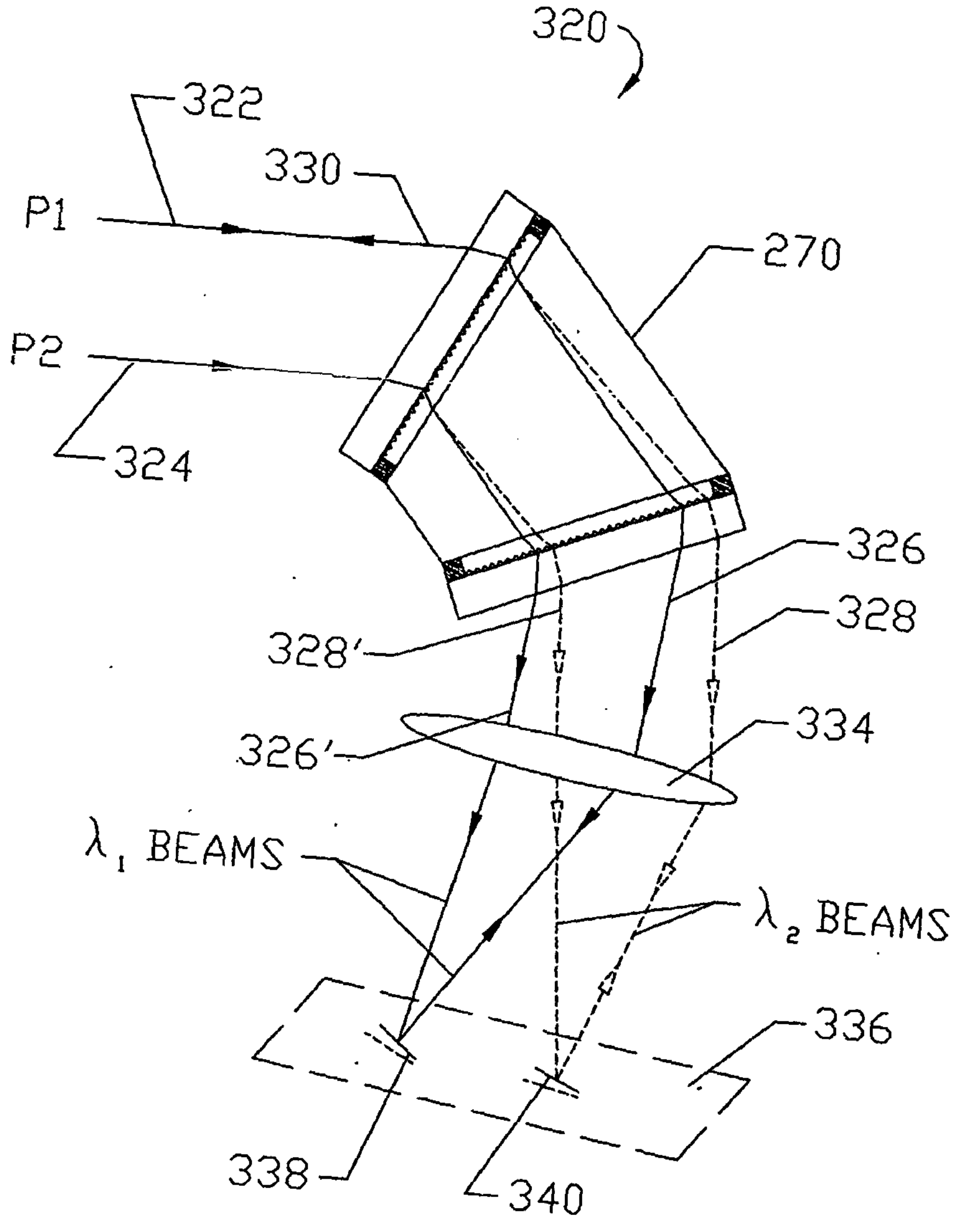
320
322
330
P1
270
P2
324
326
328
328'
334
326'
λ_1 BEAMS
λ_2 BEAMS
336
338
340

FIGURE 25A

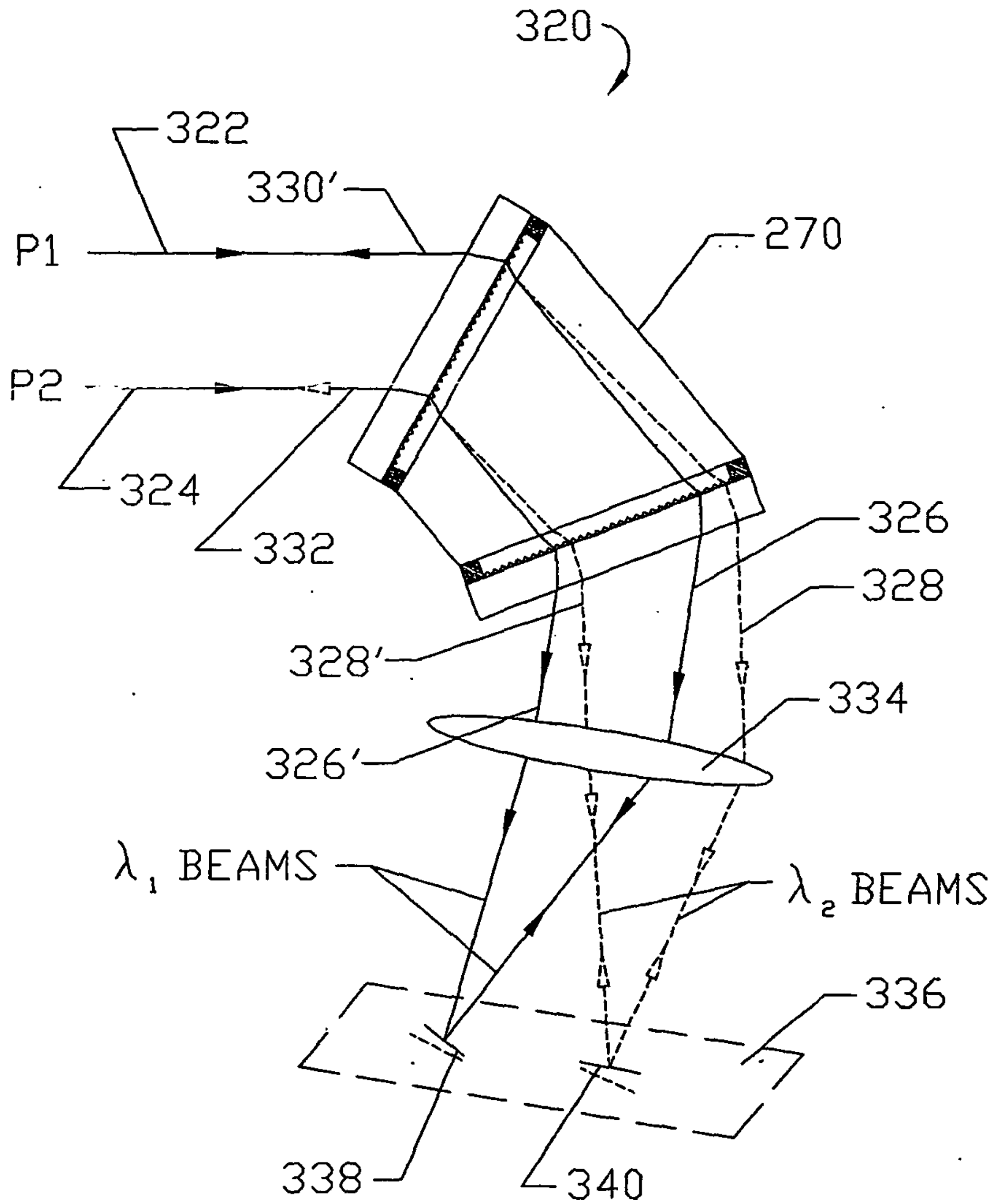
320
322
330′
270
P1
P2
324
332
326
328
328′
334
326′
λ_1 BEAMS
λ_2 BEAMS
336
338
340

FIGURE 25B

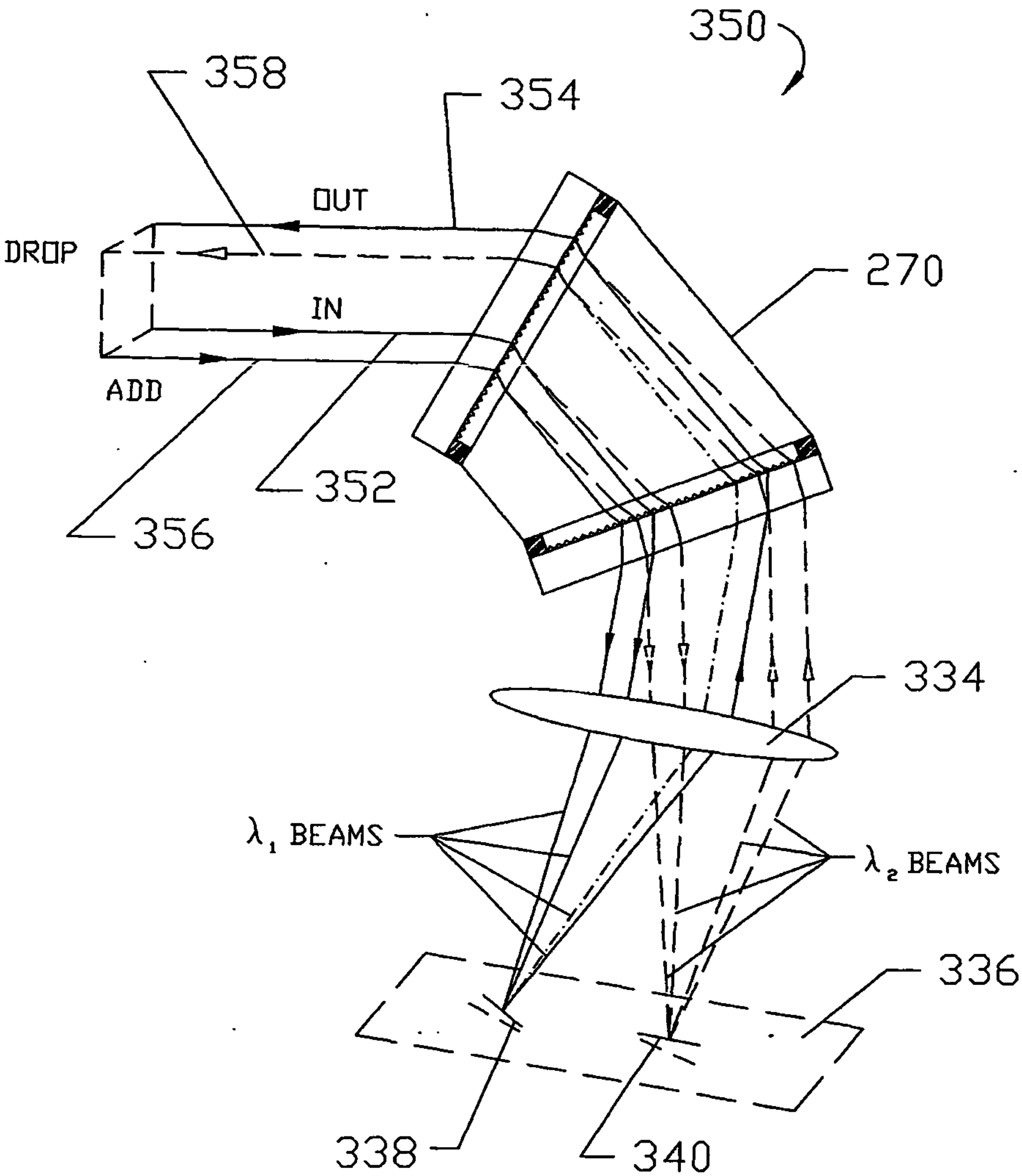
350
358
354
OUT
DROP
IN
ADD
270
352
356
334
λ_1 BEAMS
λ_2 BEAMS
336
338
340

FIGURE 26

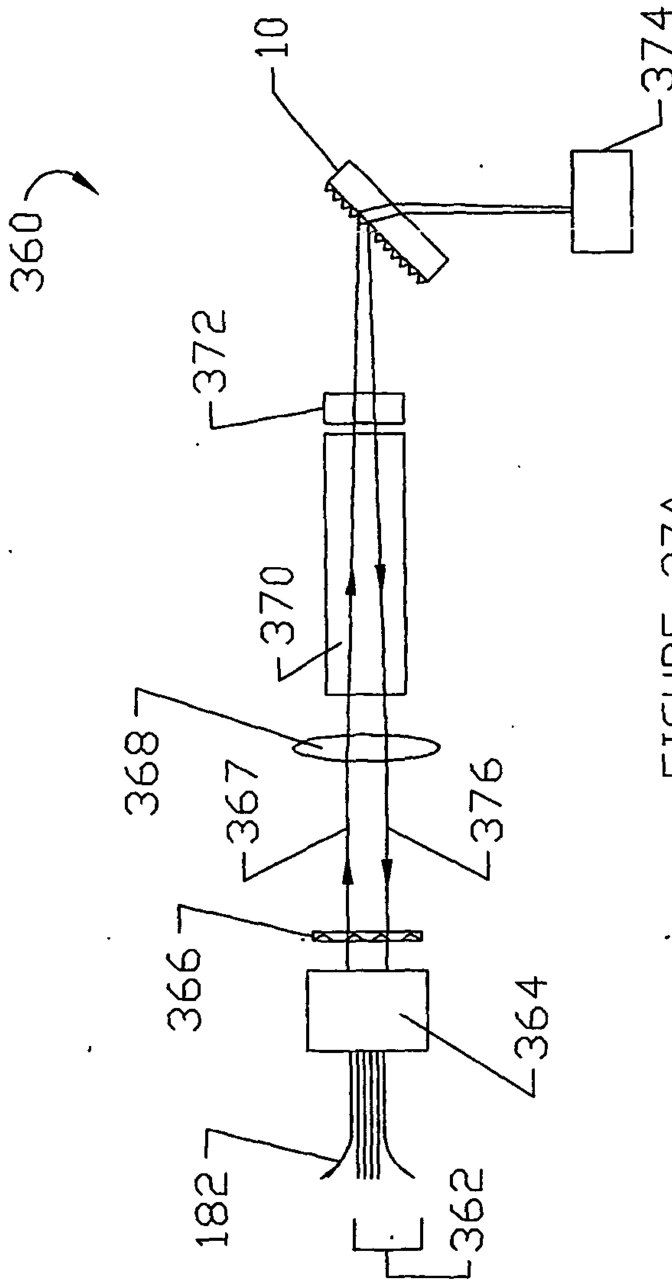

FIGURE 27A

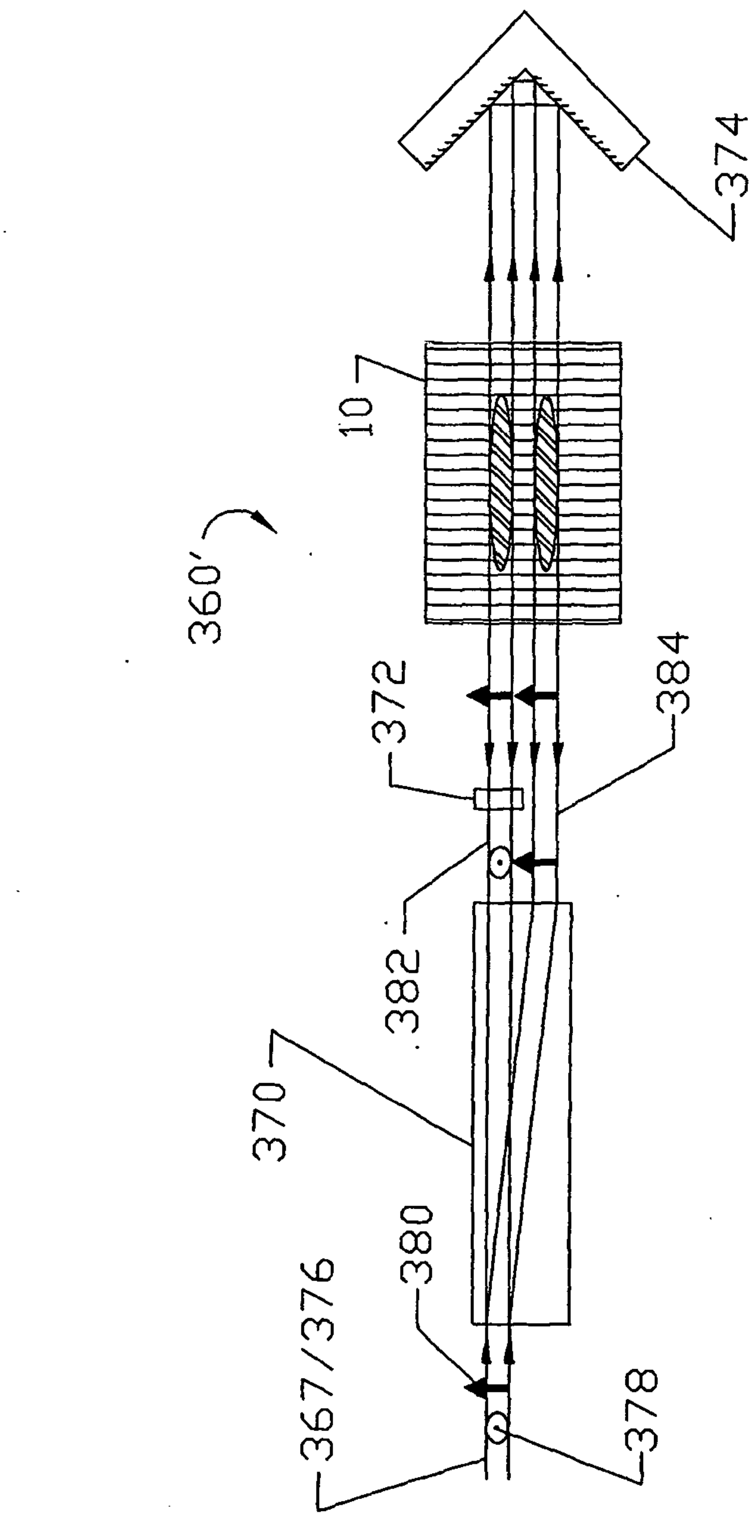

FIGURE 27B

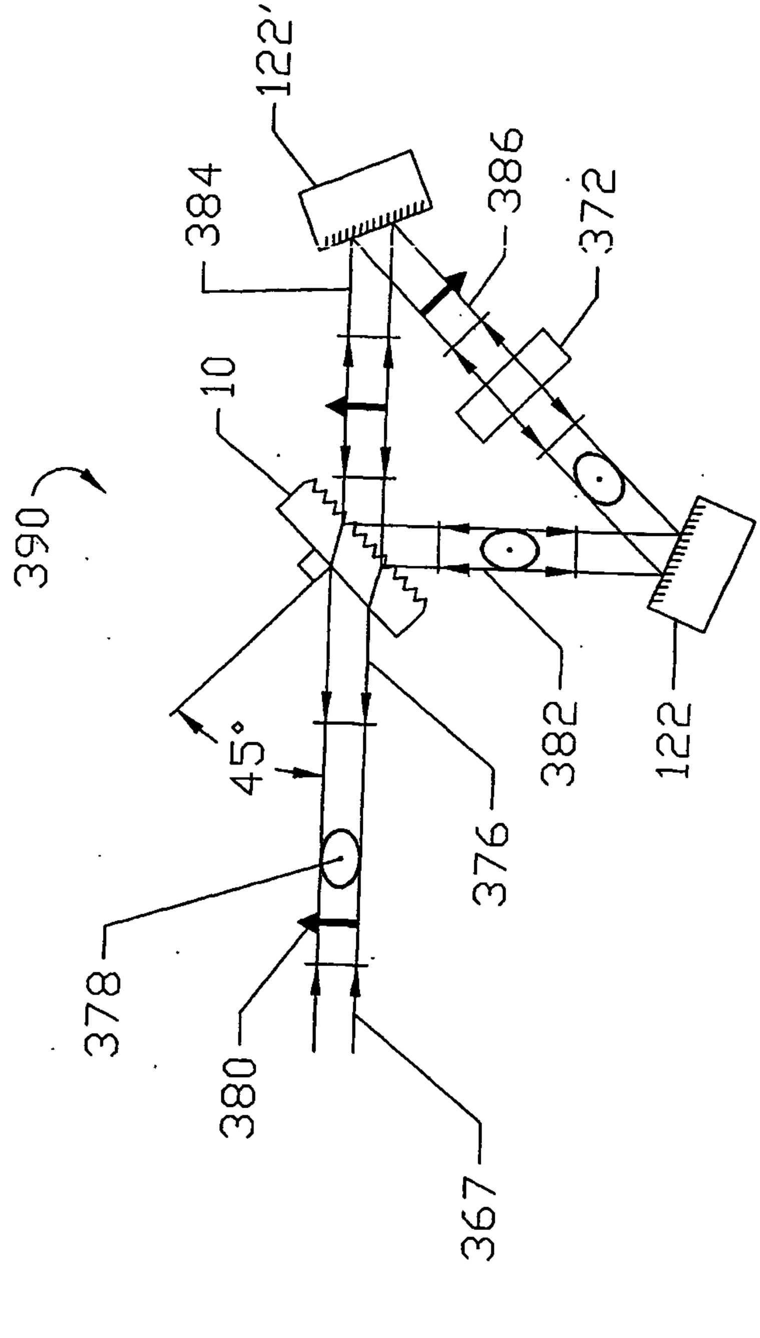

FIGURE 28